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Ancient mantle plume components constrained by tungsten isotope variability in arc lavas

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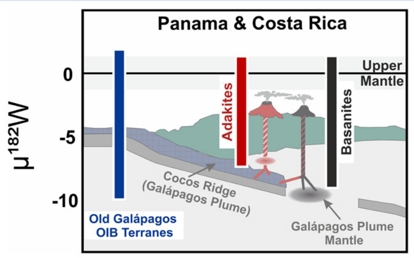
Abstract



Tungsten isotope anomalies in modern rocks are exclusively associated with plume-related basalts and may provide a unique tool to identify recycled plume material in subduction zone magmatism. In Central America, the Cocos and Coiba Ridges are subducting with the Cocos plate. These ridges may introduce material into the arc magma source that was derived from the Galápagos plume, which has been shown to carry anomalous ^{182}W signatures. Here, we report negative $\mu^{182}W$ values together with trace element data for <5 Ma old adakites and back-arc basanites, as well as accreted basalt terranes that formed as a result of Galápagos plume activity in the last 70 Myr. In adakites and basanites, these $\mu^{182}W$ deficits derive from a slab melt component that dominates the W budget of their source. In addition, negative $\mu^{182}W$ in accreted mafic terranes attest to the longevity of the primordial W isotope signature in the Galápagos plume and the involvement of a Galápagos-related magma source in the Central American arc system over time.

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Introduction

Mass transfer from variable components of the subducting oceanic lithosphere into the arc mantle and subsequent incorporation into arc magmas represents a major paradigm in Earth Sciences. While there is strong evidence for the involvement of fluids and subducted sediments in the mantle source of many arc magmas (Tera *et al.*, 1986), the nature of direct contributions of subducted basaltic crust remains debated. However, slab melting under certain conditions has become central to many models of subduction zone processes (*e.g.*, Yogodzinski *et al.*, 2015). Here, we use isotope and concentration data for W in arc-related rocks to trace slab- and plume-derived source components in arc magmas. Variations in the distribution of ^{182}W in terrestrial rocks must have been established within the first 50 Myr of Earth's history due to the short half-life of its extinct parent isotope ^{182}Hf (*e.g.*, Willbold *et al.*, 2011). The only known modern setting exhibiting negative ^{182}W variability is ocean islands associated with deep-seated mantle plumes, such as Galápagos (*e.g.*, Mundl-Petermeier *et al.*, 2020). In this context, the Central American arc system is a prime location for using W isotopes as a tracer for oceanic crust and plume-mantle components in arc magmas. Here, the 13 to 15 Ma old Cocos and Coiba Ridge (CCR), and other hotspot traces related to the Galápagos plume, are being subducted along the Panama–Costa Rica section of the Central American arc system (Hauff *et al.*, 2000; Abratis and Wörner, 2001; Gazel *et al.*, 2009, 2011). About 1.5 to 5 Ma old adakitic lavas from Panama and Costa Rica are of particular interest, since involvement of a slab melt component in their petrogenesis has previously been proposed (*e.g.*, Defant *et al.*, 1991; Abratis and Wörner, 2001; Gazel *et al.*, 2009). Identification of negative W isotope anomalies in these adakites would thus provide a strong, first-hand indication for the involvement of plume-derived subducted oceanic crust in arc melts from the Central American arc system. Further, a suite of alkaline mafic lavas (basanites) in the back-arc in Costa Rica dated at 4 to 6 Ma possibly record a mantle contribution from the Galápagos plume (Abratis and Wörner, 2001). Here, radiogenic W isotope systematics provide a powerful tracer to identify different source components that may be derived from the Galápagos plume.

Samples and Methods

We selected 14 well-characterised adakites from the Costa Rica and Panama arc front and five basanites from behind the volcanic arc of southern Costa Rica for W isotope and trace element analysis. To constrain the isotopic composition of subducted material we also analysed ocean island basalt (OIB) terranes that were accreted to the forearc of Costa Rica and Panama. The latter were interpreted to represent 18 to 71 Ma old hotspot tracks of the Galápagos plume (*e.g.*, Appel *et al.*, 1994; Hauff *et al.*, 2000; Wegner *et al.*, 2011; Gazel *et al.*, 2018). Further details on the samples as well as Sr, Pb and Nd isotope compositions can be found in Appel *et al.* (1994), Abratis and Wörner (2001) and Wegner *et al.* (2011). The W isotopic compositions are reported as $\mu^{182}W$, representing the part per million deviation of the $^{182}W/^{184}W$ ratio of a sample from W standard NIST 3163. Detailed descriptions of methods and analytical results are provided in the Supplementary Information.

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Results and Discussion

The adakites range in SiO_2 content between 53 to 69 wt. % and show high Sr/Y ratios from 100 to 200 at low Y concentrations of 7 to 14 µg/g. They feature prominent depletions in high field strength elements (HFSE) and are low in heavy rare earth elements (HREE) due to melting of hydrous meta-basalt with residual rutile and garnet (Figure S-1; Martin *et al.*, 2005). Their W isotopic compositions range from $\mu^{182}W = -6.89 \pm 2.95$ to $+0.87 \pm 2.95$ (external reproducibility, 2 s.d.). There are no observable correlations between $\mu^{182}W$ and either major or trace element concentrations, their ratios or with any radiogenic isotope ratios. Basanites have SiO_2 concentrations from 43 to 47 wt. % with high MgO of 6.3 to 9.3 wt. %. They show trace element patterns that are strongly enriched in incompatible elements with notable depletions in HFSE comparable to the adakites. Although their Sr/Y ratios are elevated compared to normal arc lava and range between 42 and 120, they also have high Y concentrations (17.5 to 30 µg/g) and are silica-undersaturated, which places them outside the compositional range expected for adakitic rocks (Martin *et al.*, 2005). Values for $\mu^{182}W$ range from -9.04 ± 4.32 to $+1.74 \pm 4.32$. Similar to the adakites, no correlations with other chemical or radiogenic isotope tracers can be observed. Accreted OIB have MgO concentrations ranging from 6 to 21 wt. %. Trace element patterns show typical intraplate affinities, similar to the modern Galápagos archipelago with enriched incompatible elements and a relative depletion in Pb. Their $\mu^{182}W$ ranges from -9.72 ± 4.8 to $+0.98 \pm 2.95$. Thus, as a first-order observation, all three rock types related to the Costa Rica–Panama subduction zone show resolvable W isotope deficits. In the following, we will address likely scenarios that can reconcile this observation.

Previous results for modern basalts from the Galápagos archipelago, together with our own data for the accreted OIB terranes, provide an approximation of the isotopic composition of the basalts from the CCR, that are currently subducted below Central America. A chemical and isotopic zonation within the Galápagos plume (Hoernle *et al.*, 2000) is mirrored by contrasting negative W isotopic compositions of basalts from the central and eastern domains of the Galápagos islands ($\mu^{182}W = -22$ and -5, respectively; Mundl-Petermeier *et al.*, 2020). This chemical zonation is also reflected in the CCR, as well as in the basaltic rocks accreted in the Central American forearc (Gazel *et al.*, 2018 and references therein). We find that the W isotopic compositions of the accreted CCR rocks analysed here do not fully reflect the entire range observed in the modern Galápagos archipelago. However, $\mu^{182}W$ deficits of up to -9.72 ± 4.80 confirm that the Galápagos plume is isotopically variable and, more importantly, show that the incorporated primordial W isotopic signature has existed for at least the past 70 Myr. This implies that the unusual W isotopic signature is a long-lived, persistent characteristic of the plume. If equivalents of such basaltic rocks from the CCR are also subducted to the depth where magmas are formed, these arc magmas would also be expected to show similar $\mu^{182}W$ deficits.

This is, in fact, supported by our observations: the $\mu^{182}W$ deficits of up to -6.89 ± 2.95 in the adakites cover almost the entire range of $\mu^{182}W$ variations measured in the accreted CCR basalts, providing a clear indication for involvement of a Galápagos plume component in their source. We will now test whether partial melts of the subducted basalts from the CCR contributed to the $\mu^{182}W$ deficits or, alternatively, the mantle wedge below Costa Rica and Panama contained material from the Galápagos plume, as was proposed for the origin of the basanites (Abratis and Wörner, 2001). The geochemical behaviour of W in subduction zones is best studied using W/Th ratios (König *et al.*, 2008). Bulk partition coefficients of W and Th are very similar during mantle melting (Arevalo and McDonough, 2008), resulting in only small variations of W/Th ratios in oceanic basalts (MORB = 0.09 to 0.24, OIB = 0.08 to 0.19; König *et al.*, 2011; Kurzweil *et al.*, 2019). During differentiation of mafic magmas, this ratio should remain constant. However, W is mobile in subduction zone fluids (Bali *et al.*, 2012), resulting in elevated W/Th ratios in arc magmas compared to MORB and OIB (Fig. 1; König *et al.*, 2008; Stubbs *et al.*, 2022). Indeed, W/Th ratios for "normal" arc lavas from Central America, with W/Th ranging from 0.05 to 0.43, fall into the global arc magma range (Fig. 1). In contrast, adakites and basanites show surprisingly low W/Th ratios between 0.02 and 0.06, substantially lower than MORB, OIB and most arc front lava previously measured. Only five of the 19 adakites and basanite samples have elevated W/Th (>0.09). These also record high Ba/Th ratios of >280 or high $^{87}Sr/^{86}Sr$ ratios of >0.704, in line with additional fluid or sedimentary components in their source (Fig. 1, Table S-1; Stubbs *et al.*, 2022). Neither involvement of slab fluids, nor the addition of an enriched mantle source, can explain the exceptionally low average W/Th ratios in the remaining adakites and basanites, because such components would result in higher, not lower, W/Th ratios. On the other hand, such low W/Th ratios could be due to melting of subducted basalts with residual rutile, where rutile preferentially retains W and other HFSE (Rudnick *et al.*, 2000; Zack *et al.*, 2002; Bali *et al.*, 2012). Strong depletions of Nb, Ta and Ti in adakites and basanites also make a strong case for the involvement of rutile (Fig. S-1). Moreover, elevated Nb/Ta ratios in both adakites (18.01 ± 1.86) and basanites (20.1 ± 1.85) compared to typical values found in oceanic basalts (Nb/Ta = 14.5 to 16.5; Gale *et al.*, 2013; Tang *et al.*, 2019) are complementary to low Nb/Ta ratios in rutile (Green and Pearson, 1987). Combined, the unusual W isotope deficits and low W/Th ratios make a strong case that the petrogenesis of adakites and basanites is linked to partial melting of a subducted metabasaltic source derived from the Galápagos plume. This either involves the slab melt directly or a mantle source modified by slab melts derived from CCR basalts.

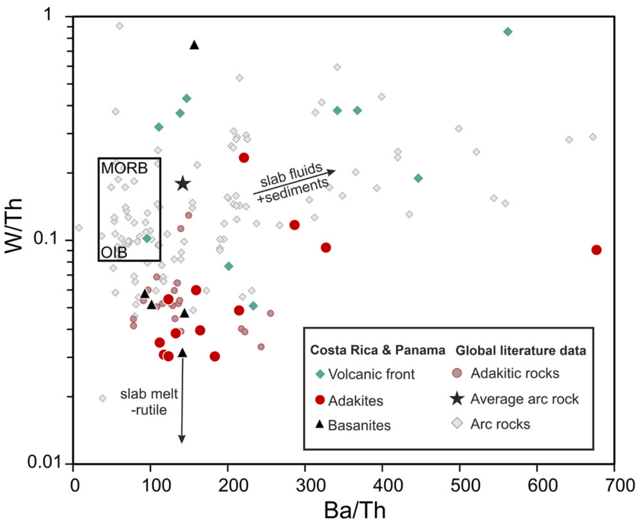

Figure 1 Fluid mobile element systematics for Panama and Costa Rica arc rocks and compiled arc data from König *et al.* (2011), Kurzweil *et al.* (2019), Mazza *et al.* (2020), and Stubbs *et al.* (2022). MORB and OIB fields defined after König *et al.* (2011) and Kurzweil *et al.* (2019). Adakitic rocks from Laeger *et al.* (2013) and Straub *et al.* (2015).

Based on the large range of silica content, it was argued that the adakites in Costa Rica and Panama do not represent pure slab melts, but rather derive from a mantle wedge metasomatised by slab melts (Gazel *et al.*, 2009, 2011; Martin *et al.*, 2005). To test this model with our data, we performed simple mixing calculations between a slab-derived melt and a subduction-modified mantle wedge (Fig. 2; see Supplementary Information for model parameters). The source of adakites is best represented by a mantle wedge metasomatised by 3 to 20 wt. % of a slab melt with low W/Th of 0.018. This is in good agreement with previous models using radiogenic isotopes (Gazel *et al.*, 2009). The variability of $\mu^{182}W$ in the adakites and the lack of correlation with other geochemical parameters require that the slab was heterogeneous in $\mu^{182}W$. Therefore, this model constrains the maximum W isotope deficit of a slab melt necessary to explain the range observed in the adakites. As shown in Figure 3a, assuming $\mu^{182}W$ values varying between −12 to 0 for the subducted CCR basalts can reconcile the isotopic compositions of most adakites. Three samples with high Ba/Th and W/Th, however, plot outside of this plausible mixing field, which is likely due to an additional component in their source.

To account for the enriched trace element signature observed in the basanites, we included an enriched source model component in our calculations. Following slab window formation below Costa Rica and Panama, previous models have argued for the ascent and decompression melting of a mantle component that was derived from the Galápagos plume as the source for the basanites (Abratis and Wörner, 2001; Gazel *et al.*, 2011). However, similar to the case of the adakites, the low W/Th ratios of the basanites require an additional slab melt component. In our model, the enriched mantle composition was estimated from the average Galápagos basalt. Melting of this enriched mantle modified by 2 to 10 wt. % slab melt formed from CCR basalts can explain the observed incompatible element enrichment in basanites while maintaining their low W/Th ratios (Figs. 2, S-2). Finally, we can test how this enriched Galápagos mantle influences the W isotopic composition of the basanites. Model A in Figure 3b uses the enriched mantle composition assuming $\mu^{182}W = 0$, while model B involves a Galápagos mantle with $\mu^{182}W$ as low as −6. Each model encompasses the observed

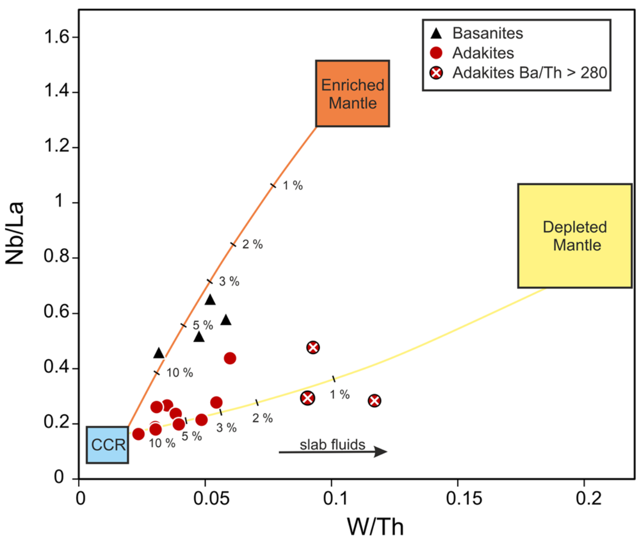

Figure 2 Two component mixing models for melts derived from a depleted mantle or an enriched mantle modified by Cocos and Coiba Ridge (CCR) melts. Endmember compositions and model parameters can be found in the Supplementary Information. Samples with W/Th > 0.2 not shown.

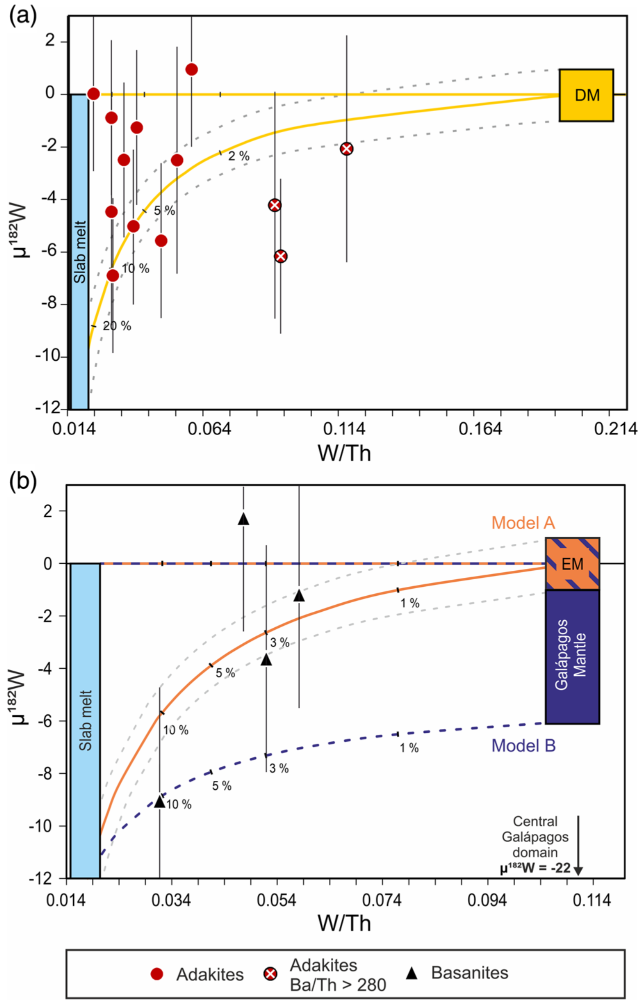

Figure 3 Two component mixing models between modelled slab melt and three different mantle compositions: **(a)** mixing with depleted mantle to model the W isotope composition of adakites and **(b)** mixing with two types of enriched mantle (models A and B) to produce the source composition of basanites. Grey dashed lines represent the error of the W isotopic composition of the upper mantle. Model parameters can be found in the Supplementary Information.

basanite compositions including the most anomalous basanite ($\mu^{182}W = -9.04 \pm 4.32$). Model A, however, shows that contributions of isotopically anomalous W from the enriched mantle source are not required to explain the variability observed in the basanites. If this mantle source is characterised by depletions in $\mu^{182}W$, values cannot be significantly lower than −6, as it is shown in model B. It is therefore unlikely that this component reflects the composition of the modern central Galápagos domain (Bekaert *et al.*, 2021). In any case, the negative W isotope signal observed in adakties and basanites from Costa Rica and Panama requires a slab melt component that carries the anomalous $\mu^{182}W$ from the Galápagos plume.

Conclusions

The tungsten isotope systematics of the adakites verify melting of subducted oceanic crust at mantle depth in the Central American arc system. Melts derived from a hybridised mantle wedge with negative $\mu^{182}W$ signatures provide strong evidence that this contribution is related to Cocos and Coiba Ridges

(CCR). In the case of the back-arc basanites, this signature is possibly modified by mantle components derived from the Galápagos plume, although their contribution is not strictly required to explain their isotopic budget. Unusually low W/Th in both adakites and basanites imply control by residual rutile on the W budget of their sources. These observations further strengthen previous proposals for magma genesis for these adakites and basanites related to the evolution of a slab window below Costa Rica and Panama as a consequence of CCR collision with the Central American subduction zone. Finally, we document that the anomalous low $\mu^{182}W$ signal is a long-lived (>70 Myr) geochemical signature of the Galápagos plume.

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Additional Information

Supplementary Information accompanies this letter at https://www.geochemicalperspectivesletters.org/article2321.

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