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Hafnium isotope evidence for slab melt contributions in the Central Mexican Volcanic Belt and implications for slab melting in hot and cold slab arcs

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A B S T R A C T

This study presents evidence that Quaternary frontal arc calc-alkaline lavas from Central Mexican Volcanic Belt (CMVB) contain contributions from partial melts of the subducting garnet-bearing eclogitic oceanic crust and sediment, based on chemical and Hf–Nd isotope data. The CMVB includes both calc-alkaline lavas with arc-type trace element patterns such as aqueous fluid mobile element enrichments and high field strength element depletions; and "high-Nb" alkaline lavas with trace element patterns similar to ocean island basalts. The two types of lavas are closely related geographically and temporally. Distinct from the high-Nb lavas, the calc-alkaline lavas show trends toward higher $^{176}Hf/^{177}Hf$ and $^{143}Nd/^{144}Nd$ ratios coupled with lower Lu/Hf. The high Hf–Nd isotope ratios fingerprint contributions of subducted basaltic ocean crust, while the correlation with low Lu/Hf indicates melting in the presence of residual garnet, which reflects conversion of the subducted oceanic crust to eclogite. Isotopic and chemical mass balance considerations indicate that the slab melts are ~80% basaltic oceanic crust and ~20% subducted sediment. The calc-alkaline lavas have higher SiO_2 at a given Mg# compared to the high-Nb alkaline lavas, also reflecting melt contributions from the subducted slab.

A survey of global arc lavas shows that calc-alkaline lavas with low Lu/Hf ratios, reflecting melting in the presence of residual garnet and preferential mobilization of Hf over Lu from the subducted slab, are generally associated with hot slab conditions. These include arcs where young (<30 Ma old) ocean crust is subducted (*e.g.* Mexican Volcanic Belt, Cascades, Austral Andes, Luzon, Setouchi), where slab tearing occurred and hot asthenospheric mantle could upwell through the slab window (*e.g.*, western Aleutians, Sunda, southern Scotia), and where oblique or slow subduction leads to higher slab temperatures (*e.g.* Lesser Antilles, western Aleutians). In some of these hot slab arcs, where low Lu/Hf ratios are coupled with high Nd–Hf isotope ratios, slab melt contributions are dominated by partial melts from the subducted oceanic basalt (*e.g.*, Mexican Volcanic Belt, Aleutians and Cascades). In other hot slab arcs, low Lu/Hf ratios are coupled with low Nd–Hf isotope ratios, reflecting slab contributions dominated by sediment melts (*e.g.* Setouchi, Lesser Antilles, Luzon, Sunda, and southern Scotia). Arcs associated with colder subducted oceanic crust (*e.g.* Izu–Bonin–Marianas, Tonga–Kermadec, central and northern Scotia) erupt lavas with high Lu/Hf along with high Hf–Nd isotope ratios, similar to mid-ocean ridge basalts, thus they lack the signature of residual garnet as well as significant slab melt input.

1. Introduction

Magma genesis at convergent plate margins has long been attributed to fluxing of the mantle wedge by "solute-rich" fluids containing significant amounts of H_2O, derived from the subducting oceanic crust and sediments (*e.g.*, Morris et al., 2003; Plank et al., 2009). These fluids also impart distinctive geochemical signatures to arc magmas, such as enrichments in aqueous fluid mobile elements (*e.g.*, Ba, Sr, Pb) relative to elements with limited aqueous fluid mobility, for example the rare

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earth elements (REE, *e.g.*, Sm, Nd) and the high field strength elements (HFSE, *e.g.*, Nb, Ta, Hf). It has remained unclear, however, in what capacity silicate melts of the subducted oceanic crust-sediment package contribute to the arc mantle wedge, for example, whether the subducted slab could partially melt under most arcs (*e.g.* Kelemen et al., 2003; Schmidt et al., 2004; Portnyagin et al., 2007); or whether it can only partially melt under unusually hot conditions, such as the subduction of young, hot slabs (*e.g.*, Defant and Drummond, 1990; Peacock et al., 1994), or at slab edges heated by upwelling hot asthenospheric mantle (*e.g.*, Yogodzinski et al., 1995, 2001; Thorkelson and Breitsprecher, 2005). It has also been shown that higher slab temperatures lead to increased silica polymerization and as a result, higher overall trace element mobility (Manning, 2004). Thus, high temperature silica-rich "slab-melts" can be traced by elements with limited mobility in low temperature aqueous- or solute-rich fluids, such as the REE, HFSE and Th. Of particular interest are the heavy rare earth elements (HREE, *e.g.*, Lu, Yb), which are preferentially retained by residual garnet in the slab during eclogite melting.

A challenge in identifying subduction contributions in arc lavas arises from compositional similarities between the subducted package and the overlying mantle-crust assemblage. For example, sediment melt contributions could impose elevated Si content and crustal-like isotope signatures on arc lavas, which resemble the effects of shallow level assimilation-fractional crystallization (AFC) processes (*e.g.*, Hildreth and Moorbath, 1988). Hf–Nd isotopes can be used to identify hydrothermal sediment melt contributions in arcs owing to their distinct Hf–Nd isotope compositions. In Hf–Nd isotope space, most terrestrial rocks (e.g., mafic and felsic volcanics, and clastic sediments) fall on a well-defined "mantle–crust array" (*e.g.* Vervoort et al., 1999, 2011), while hydrothermal sediments fall on a "seawater array", which intersects the "mantle–crust array" at an angle, with higher $^{176}Hf/^{177}Hf$ ratios for a given $^{143}Nd/^{144}Nd$ ratio (Albarède et al., 1998). Melt contributions from subducted hydrothermal sediments could thus generate deviations from the "mantle–crust array" towards the "seawater array" in arc lavas (*e.g.*, Marini et al., 2005; Handley et al., 2011). Moreover slab-derived melt contributions must also be distinguished from melts of the lower crust beneath an arc, which can be evaluated based on relationships between Hf–Nd isotope ratios and high field strength element ratios (*e.g.*, Nb/Ta and Zr/Hf) (*e.g.* Gómez-Tuena et al., 2003; Pfänder et al., 2007; Gómez-Tuena et al., 2011; Pfänder et al., 2012).

Volcanism in the Central Mexican Volcanic Belt (CMVB) is associated with the subduction of the young (14-18 Ma) Cocos Plate (at ~6 cm/year) (Fig. 1; Pardo and Suárez, 1995). The Mexican Volcanic Belt trends oblique to the trench, which reflects an unusual subduction geometry, whereby the subducting Cocos Plate flattens northward and remains at a shallow depth of ~40 km for about 200 km, before it bends down at ~75° angle just below the arc front (Pérez-Campos et al., 2008). Besides subduction of a young, hot oceanic plate, the unusual subduction geometry may also lead to higher slab temperatures given the increased coupling surface between the flat slab and the overlying plate (Manea et al., 2004, 2005). Thus, the CMVB provides an excellent framework to test for slab melting using geochemical tracers.

Evidence for slab melt contributions in the CMVB has been reported in previous studies (*e.g.*, Gómez-Tuena et al., 2003; Martínez-Serrano et al., 2004; Gómez-Tuena et al., 2007; Mori et al., 2007; Gómez-Tuena et al., 2008), although the same types of observations have also been used to argue for crustal assimilation (*e.g.*, Siebe et al., 2004; Schaaf et al., 2005; Torres-Alvarado et al., 2011). However these studies did not report Hf isotope ratios which, as we show here, add important supporting evidence for slab melt contributions. In this study we evaluate the role of slab melting beneath the CMVB with new Hf–Nd isotope and elemental data. To further demonstrate the validity and implications of our findings we also compare our CMVB observations with global arcs.

2. Geologic background

The CMVB is constructed on 45–50 km of continental crust composed of Mesozoic marine sediments overlying Proterozoic granulitic lower crust (Schaaf et al., 1994; Ortega-Gutiérrez et al., 1995;

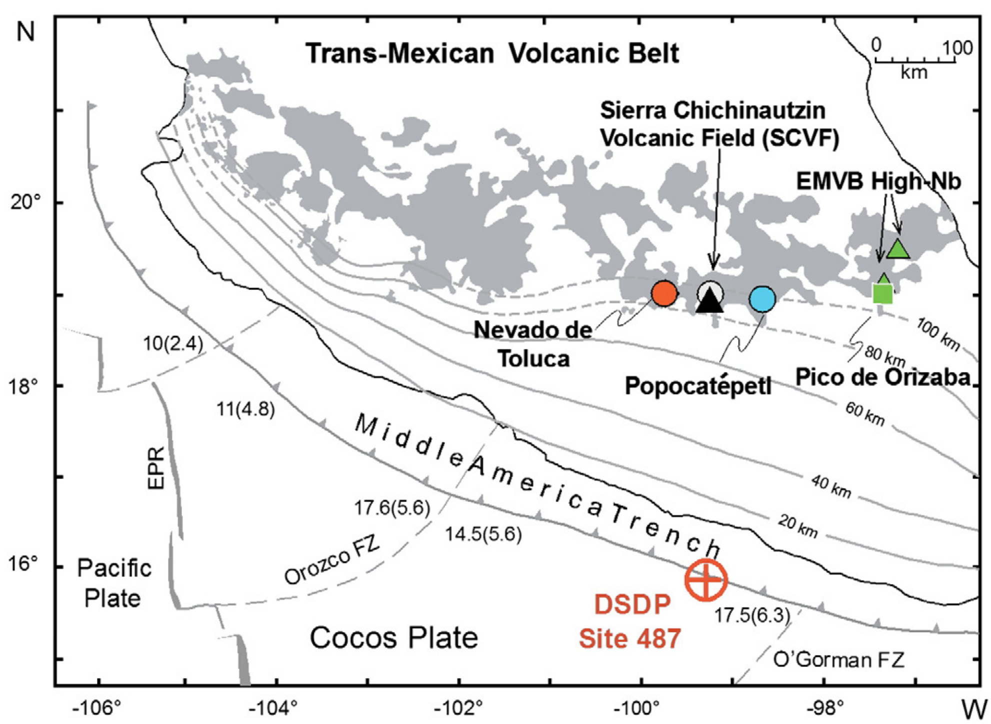

Fig. 1. Schematic map of the studied areas in the context of the Quaternary Trans-Mexican Volcanic Belt (highlighted in dark gray) overlain by contours of inferred slab depth (Pardo and Suárez, 1995). Also shown is the location of DSDP Site 487. "High-Nb" lavas (in triangles) are found in Sierra Chichinautzin Volcanic Field (SCVF) as well as in the Eastern Mexican Volcanic Belt (EMVB) from monogenetic centers near stratovolcano Pico de Orizaba. Other symbols are: EPR = East Pacific Rise; FZ = fracture zone. Along the Middle America Trench, ages of the subducting Cocos plate are marked in millions of years, followed by the convergence rates in parentheses in cm/year (Demets et al., 1990).