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Mantle–crust interactions in a paleosubduction zone: Evidence from highly siderophile element systematics of eclogite and related rocks

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ABSTRACT

Substantial differences in $^{187}Os/^{188}Os$ and absolute and relative abundances of highly siderophile elements (HSE: Os, Ir, Ru, Pt, Pd, Re) in mantle peridotites compared to oceanic crust indicate that this suite of elements may prove useful in assessing mechanisms and pathways of mantle and slab mass transfer within the subduction channel. Currently, however, information regarding the mobility of the HSE in subduction zone environments is limited. To better understand the systematics of highly siderophile elements in subduction settings, we measured Os isotopic compositions and HSE abundances of cores and rinds of meter-scale blocks of eclogite, blueschist and garnet amphibolite from subduction-related mélanges within 1) the Franciscan Complex, CA, and a related terrane in Oregon; 2) the Catalina Schist, CA; and 3) the Samana Metamorphic Complex, Samana Peninsula, Dominican Republic. Rinds composed of amphibole, chlorite, ± phengite, talc, titanite and rutile partly enclose blocks at each location. Mineralogic, petrologic and geochemical data suggest that these rinds are metasomatic features that formed by fluid-mediated interaction between mafic blocks and an ultramafic matrix.

The cores of high-grade blocks are characterized by high (Pt + Pd)/(Os + Ir + Ru), and variably radiogenic Os; initial $^{187}Os/^{188}Os$ ranges from 0.197 to 4.30. These characteristics are consistent with the HSE compositions of subducted basalts. In contrast, (Pt + Pd)/(Os + Ir + Ru) of rinds are generally much lower than cores, approaching values typical of mantle peridotites. The initial $^{187}Os/^{188}Os$ of most rinds are also typical of upper mantle peridotites; values for most rinds fall between 0.125 and 0.14. The similarities of the $^{187}Os/^{188}Os$ and HSE abundances between rinds and mantle peridotites indicate that the HSE contained within rinds reflect a contribution by mantle peridotite, whether by fluid-mediated transfer or through mechanical processes. If the HSE signatures of the rinds were generated by fluid-mediated metasomatic processes, these data require remarkably efficient and uniform transference of mantle HSE from peridotitic mélange matrix to the exteriors of mélange blocks during rind formation. More likely, the rinds are coatings of materials that contain HSE derived from peridotite precursors. These results suggest that centimeter-scale mass transfer by physical mechanisms may be important for some elements within the subduction channel.

1. Introduction

In a subduction zone, rocks that comprise the subducting slab and the overlying mantle wedge may have drastically different chemical and isotopic compositions. This compositional diversity can be exploited to trace subduction zone components from different rock types, through metamorphic processes, and ultimately into arc magmas (e.g., Alves et al., 1999; Davidson, 1996; Elliott, 2003; Gill, 1981; Hawkesworth et al., 1993; Morris and Ryan, 2003; Plank and Langmuir, 1993). Subduction-related metamorphic rocks also show evidence for a variety of processes occurring within the "subduction channel," the dynamic interface between the subducting slab and the overlying mantle wedge (Cloos and Shreve, 1988a,b; Gerya et al., 2002; Shreve and Cloos, 1986), that act to hybridize these disparate crustal and mantle lithologies, including tectonic mixing and metasomatism due to fluid–rock interactions (e.g., Bebout and Barton, 1989, 2002; King et al., 2007; Nelson, 1995; Sorensen and Grossman, 1989). Chemical and isotopic tracers within metamorphic rocks can be used to elucidate these subduction zone processes (e.g., Beane and Sorensen, 2007; Bebout, 2007; Bebout and Barton, 1989; Breeding et al., 2004; Brunsmann et al., 2001; Domanik et al., 1993; John et al., 2008; King et al., 2006; 2007; Marschall et al., 2009; Miller et al., 2009; Sorensen and Barton, 1987; Sorensen and Grossman, 1989; Sorensen et al., 2006; Spandler et al., 2004; van der Straaten et al., 2008; Zack and John, 2007). The isotopic and chemical tracers currently applied to subduction systems, however, mainly provide information about the input of sedimentary and

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mafic components of the subducting slab (e.g., $^{143}Nd/^{144}Nd$, $^{87}Sr/^{86}Sr$, $\delta^{18}O$, $\delta^{11}B$, U, Th, Pb, La/Sm, and large ion lithophile elements) to arc magmas (see Elliott, 2003). Much less information is available regarding the contributions of mantle peridotite (either from slab or mantle wedge) to processes occurring at the slab–mantle wedge interface and subsequent arc magma genesis. This primarily reflects the paucity of suitable fluid- and melt-mobile tracers in peridotites.

The abundances and isotopic systematics of highly siderophile elements (HSE: including Os, Ir, Ru, Pt, Pd and Re) are investigated here as tracers of the contribution of mantle peridotites to processes of mixing, metasomatism and mass transfer occurring at the slab–wedge interface. Osmium, Ir and Ru are in general strongly compatible during mantle melting, so mantle peridotites are typically highly enriched in these elements compared to most crustal materials, including sedimentary rocks and mid-ocean ridge basalts (MORB) (e.g., Peucker-Ehrenbrink and Jahn, 2001; Peucker-Ehrenbrink et al., 2003; Rehkämper et al., 1999; Schiano et al., 1997). Platinum and Pd are in general either moderately incompatible, or little fractionated between mantle and crust. Thus, the (Pt + Pd)/(Os + Ir + Ru) ratio can potentially be used to discriminate between subducted materials with mantle peridotite provenance compared to those that originated as sediment or basalt. Rhenium is typically incompatible during mantle melting and is enriched in most crustal rocks compared to mantle peridotite. Mantle peridotite also in general displays lower $^{187}Os/^{188}Os$ ratios. Since ^{187}Os is a product of the decay of ^{187}Re ($t_{1/2} = 42$ Ga), this reflects the low Re/Os of peridotite, compared to basalts and sedimentary rocks. Consequently, in addition to HSE abundances, Os isotopic compositions can also serve as a sensitive tracer of the relative amounts of mantle versus crustal materials in subduction zone mélanges. Osmium isotopic compositions will not be sensitive to the abundance of accessory phases, which, if distributed irregularly, could affect the concentration of the HSE or other trace or minor elements used as a tracer.

The abundances of HSE and Os isotope compositions have been used to track mantle processes such as melt depletion and refertilization of peridotites (e.g., Rudnick and Walker, 2009). In particular, Os isotope compositions can record the timing of melt depletion events, because of the compatibility of Os and incompatibility of Re during the partial melting of peridotite (e.g., Walker et al., 1989). Both HSE abundances and Os isotopic compositions have also been used to track mantle metasomatism in subduction zone lithologies (e.g., arc volcanic rocks and associated mantle xenoliths; Alves et al., 1999, 2002; Brandon et al., 1996; Widom et al., 2003). Both Brandon et al. (1996) and Widom et al. (2003) measured $^{187}Os/^{188}Os$ values in peridotite xenoliths derived from above a subducting slab. In each case, $^{187}Os/^{188}Os$ values were greater than ambient depleted mantle (up to 0.134 and 0.157 compared to 0.122 to 0.129 for typical mantle peridotite). They interpreted these results to indicate that aqueous, possibly Cl-rich fluids derived from the subducting slab had metasomatized the mantle wedge, producing elevated Os isotopic ratios. This interpretation is consistent with limited experimental evidence that suggests that Os can be mobilized by solutions with elevated concentrations of Cl (Xiong and Wood, 2000). In arc volcanic rocks, relationships between Os concentrations and $^{187}Os/^{188}Os$ have been interpreted to result from mixing between a crustal contaminant and peridotite (Alves et al., 1999, 2002).

There is limited evidence from metamorphic rocks for the mobility of the HSE during metamorphism. The Re contents of mafic eclogite, blueschist and granulite samples from seven different high-pressure metamorphic belts in Europe were lower than their presumed MORB protoliths (Becker, 2000). This was attributed to Re loss during prograde metamorphic dehydration reactions. Losses of Re, Pt and Pd during Alpine metamorphism of basaltic protoliths of the Zermatt-Saas ophiolite up to eclogite facies were reported, whereas gabbroic rocks displayed evidence for only Pd mobility during eclogite facies metamorphism (Dale et al., 2007, 2009). None of these studies showed evidence for significant mobility of Os, although it could not be ruled out.

In many subduction zone metamorphic complexes around the world, eclogites and related rocks are found as isolated blocks in subduction-related mélange units. These mélange units consist of mixtures of isolated and variably deformed centimeter- to kilometer-scale blocks of metagraywacke, low-grade metabasalt, and high-grade garnet- or epidote-blueschist, eclogite and garnet amphibolite within a fine-grained matrix. The blocks sample a range of subduction zone *P*–*T* conditions. The mélange matrix is heterogeneous in composition at the centimeter- to meter-scale. Local compositions range from near-pelitic to ultramafic in composition. Mélange zones are commonly interpreted to form at various depths between a subducting slab and the overlying mantle wedge (Bebout and Barton, 1989; Breeding et al., 2004; Cloos, 1982; Gerya et al., 2002). The structural position of mélange units above a dehydrating, subducting slab makes them ideal environments for recording subduction-related processes of aqueous infiltration, melting, and tectonic mixing of crust and mantle. Mélanges thus provide windows into processes that may ultimately generate arc magmas above subducting slabs.

This study focuses on high-grade mafic blocks from mélange units from several different subduction complexes: the Franciscan Complex, CA (and an associated terrane in Oregon); the Catalina Schist, CA; and the Samana Metamorphic Complex, Dominican Republic. Blocks from all these locations have outer 'rinds' that have elevated whole-rock MgO, Cr, and Ni, relative to the mafic block cores (e.g., Cloos, 1986; Coleman, 1980; Coleman and Lanphere, 1971; Moore, 1984; Nelson, 1995; Saha et al., 2005; Sorensen and Grossman, 1989; Sorensen et al., 1997). The rinds are similar to those on blocks from many other exhumed high-*P*/*T* localities, including the Shuksan Metamorphic Suite of Washington State, USA; Syros, (Cyclades) Greece; Cima di Gagnone, Alps, Switzerland; Port Macquarie, New South Wales, Australia; and NE New Caledonia (Carson et al., 2000; Evans et al., 1979; Fitzherbert et al., 2004; Marschall et al., 2006; Och et al., 2003; Rice et al., 1974; Sorensen and Grossman, 1989, 1993; Sorensen et al., 1997; Spandler et al., 2003). Rinds have previously been interpreted to form via metasomatic interactions among blocks, ultramafic host rocks, and subduction zone fluids. The elevated MgO, Cr, and Ni contents have been interpreted as evidence that a mantle component was associated with rind formation, even for blocks and rinds with no ultramafic rocks locally present (e.g., Cloos, 1986; Coleman, 1967, 1980; Coleman and Lanphere, 1971; Moore, 1984; Nelson, 1995; Sorensen and Grossman, 1989; Sorensen et al., 1997).

Here we compare whole-rock concentrations of HSE and Os isotopic compositions of eclogite, garnet amphibolite and blueschist block cores to those of associated rinds from each of these subduction zone complexes. The HSE are used to assess the extent to which peridotitic material is mixed with crustal material at the slab–mantle wedge interface.

2. Geologic setting

High-grade blocks of blueschist, garnet amphibolite, and eclogite are found in many localities of the central belt of the Franciscan Complex, California Coast Ranges, in the amphibolite-grade mélange unit of the Catalina Schist, and on the north coast of the Dominican Republic in the Samana Metamorphic Complex (e.g., Bailey et al., 1964; Moore and Blake, 1989; Sorensen and Barton, 1987; Sorensen et al., 1997). The blocks that are the focus of this study have, for the most part, been the subjects of a number of previous mineralogical, petrological, and chemical investigations (Bebout and Barton, 1989; Catlos and Sorensen, 2003; Cloos, 1986; Giaramita and Sorensen, 1994; Moore and Blake, 1989; Nelson, 1991, 1995; Penniston-Dorland et al., 2010; Sorensen, 1988; Sorensen and Barton, 1987; Sorensen and Grossman, 1989; Sorensen et al., 1997). The Franciscan blocks are