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Boron and lead isotope signatures of subduction-zone mélange formation: Hybridization and fractionation along the slab–mantle interface beneath volcanic arcs

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Abstract

The B and Pb isotope systems are widely applied tracers of recycling processes occurring during subduction. Studies examining these complementary systems as a pair enjoy considerable success, where B primarily records the thermal and fluid evolution of the subducting slab, whereas the tripartite Pb system constrains the source of subducted material returned to volcanic arcs. However, interpretations derived from the arc volcanic record critically depend upon assumptions regarding compositions of unmetamorphosed inputs to subduction zones. Few studies have directly addressed potential fractionation of B isotopes and U–Th–Pb by analysis of high-pressure (HP) and ultrahigh-pressure (UHP) metamorphic suites, despite that fractionation in these systems during subduction-zone metamorphism has been inferred in many studies of volcanic arcs and ocean–island basalts. Here, we address the metamorphic evolution of subducted material with B and Pb isotope determinations for the mélange matrix of the Catalina Schist, CA.

Within the Catalina Schist, mélange matrix formed through the synergistic effects of metasomatism and deformation, affecting basalts and sediments derived from the subducting Farallon plate with peridotites derived from the overlying mantle wedge. Models of simple mechanical mixing among these end-members broadly predict both B and Pb concentrations within hybridized schistose mélange matrix, but an explanation of isotope ratios for both systems requires significant fractionation during metamorphism. The B isotope results are compatible with the previously presented model for sources and transport of fluid within the Catalina Schist subduction zone based on O and H isotope data: δ^{11}B values for the amphibolite facies mélange matrix are consistent with infiltration by B-bearing fluid produced in lower-T metasediment-rich domains, whereas the lower-grade lawsonite–albite and lawsonite–blueschist tectonometamorphic units represent possible analogs for the sources of this B-bearing fluid. Overall, Pb isotope ratios are indistinguishable as a function of metamorphic grade and are highly radiogenic. We constrained the potential influence of radiogenic continental detritus to the Catalina subduction zone by estimation of the continental input component from detrital zircon U–Pb age spectra. This zircon-based sedimentation proxy demonstrates that the potential influence of the Mesozoic California Andean-type convergent margin cannot in all cases explain the radiogenic Pb signature of the Catalina

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mélange matrix, seemingly requiring some fractionation of the U–Th–Pb system during formation of the lawsonite–albite and lawsonite–blueschist mélange units. Pb isotope signatures of the lower-grade mélange matrix can be explained by a two-stage metamorphic fractionation model involving early loss of Pb by desulfidation reactions, followed by deeper loss of silicate U, during subduction. Pb signatures of the amphibolite facies mélange matrix suggest either efficient retention of protolith Pb signatures during metamorphism or faithful transfer of the fractionated Pb signature by metamorphic fluid flow. Contamination of the mantle wedge by Catalina Schist B and Pb isotope fluid signatures can explain B–Pb isotope anomalies observed for modern arcs, indicating that the effects of mélange mixing should be considered in models of subduction-zone mass transfer.

Keywords: Boron isotopes; Lead isotopes; Subduction zones; Metamorphism; Mélange

1. Introduction

A long-standing goal of subduction zone research is to determine how subducted mass is redistributed between crustal and mantle reservoirs. The readily targeted "inputs" to this process include oceanic crust, pelagic sediment, and trench-fill detritus (e.g. Smith et al., 1995; Rea and Ruff, 1996; Plank and Langmuir, 1998; Hauff et al., 2003; Kelley et al., 2003). Similarly, the easily accessed "outputs" of the subduction process are the compositions of arc volcanic rocks and ocean island basalts (e.g. Ishikawa and Nakamura, 1994; Pearce and Peate, 1995; Ryan et al., 1995; Elliot et al., 1997; Ishikawa and Tera, 1999; Rosner et al., 2003; Moriguti et al., 2004; Kelley et al., 2005). Comparison of the inputs and outputs of the subduction process has given rise to explicit predictions regarding the role of metamorphic processes in redistributing subducted mass between the crust and mantle during subduction (e.g., Chauvel et al., 1995; Bach et al., 2003; Kelley et al., 2005). To evaluate these predictions, it is necessary to directly examine subduction zone rocks for evidence of how mass is redistributed during metamorphism (e.g. Sorensen and Barton, 1987; Bebout, 1991, in press; Bebout and Barton, 1989, 1993; Sorensen and Grossman, 1989, 1993; Bebout et al., 1993, 1999, 2007-this issue; Zack et al., 2002; Chalot-Prat et al., 2003; Spandler et al., 2003, 2004; King et al., 2003, 2004, 2006; Marschall et al., 2006, 2007-this issue; Zack and John, this volume).

Boron and Pb isotope systematics have proven to be of great value in studies undertaken to address recycling of subducted mass back into the crust. Although B and Pb are equivalently mobile in slab-derived fluids, the processes that govern their mobility appear to differ significantly. For example, redistribution of B and fractionation of its isotopic species is known to be a strong function of the thermal evolution and resulting devolatilization history of subducted materials (e.g., Moran et al., 1992; Bebout et al., 1993, Peacock and Hervig, 1999; Nakano and Nakamura, 2001; Bebout and Nakamura, 2003; Marschall et al., 2007-this issue). Alternatively, whereas Pb isotopic data are widely believed to preserve the signature of the subducted protolith (e.g., Hauff et al., 2003), few studies have explicitly examined this (Usui et al., 2006). This is unfortunate, particularly in light of predicted metamorphic U–Th–Pb fractionation during subduction (Chauvel et al., 1995; Bach et al., 2003; Kelley et al., 2005).

There is growing appreciation that mass transfer within enhanced permeability structures such as mélange zones and fracture systems may dominate slab-derived signatures transferred to the mantle wedge (Bebout and Barton, 2002; Breeding et al., 2004; John et al., 2004; King et al., 2006; Ague, 2007-this volume; Zack and John, 2007-this volume) relative to the impact of less-deformed subducted lithologies (e.g., Chalot-Prat et al., 2003; Spandler et al., 2003, 2004; Spandler and Hermann, 2006). Based on extensive O–H–N isotopic study, mélange zones have been shown to represent zones of greatly enhanced fluid flow that are characterized by pervasive stable isotope homogenization and extensive redistribution of many major and trace elements (Bebout, 1991, 1997; Bebout and Barton, 1993, 2002). In this paper, we examine the B and Pb isotopic systematics of mélange present within a deep-seated accretionary complex (Catalina Schist, CA, USA) to gain insights into the evolution of these systems during subduction. In our consideration of Pb isotope behavior in these units, we utilize detrital zircon U–Pb age distributions (Grove et al., in press) to help us deduce the time-dependent variation of the Pb isotopic composition of trench-fill sediment derived from the adjacent mid-Cretaceous arc and continental domain. These data help us to resolve the disparate behavior of the B and Pb isotope systems during subduction metamorphism, allowing for a more complete view of how these geochemically important tracers are redistributed during subduction.