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Geochimica et Cosmochimica Acta 217 (2017) 462–491

Geochimica et Cosmochimica Acta

www.elsevier.com/locate/gca

Tracing subducted sediment inputs to the Ryukyu arc-Okinawa Trough system: Evidence from thallium isotopes

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Received 8 February 2017; available online 1 September 2017

Abstract

Sediments are actively subducted in virtually every arc worldwide. However, quantifying their contributions to arc lavas and thereby establishing budgets of how sediments participate in slab-mantle interaction is challenging. In this contribution we use thallium (Tl) abundances and isotopic compositions of lavas from the Ryukyu arc (including south Kyushu) and its back-arc basin, Okinawa Trough, to investigate the influence of sediments from arc to back-arc. We also present extensive geochemical data for sediments and altered oceanic crust (AOC) outboard of the northern (DSDP Sites 296, 442B, 443 and 444) and central (DSDP Sites 294 and 295) part of the Ryukyu arc. The Tl isotopic compositions of sediments change systematically from lighter outboard of northern Ryukyu arc to heavier outboard of central Ryukyu arc. The feature reflects the dominance of terrigenous material and pelagic sedimentation outboard of the northern and central Ryukyu arc, respectively. Central and northern sections of Ryukyu arc and Okinawa Trough display larger range of Tl isotopic variation than southern section, which is consistent with more pelagic provenance for sediments outboard of central and northern Ryukyu arcs than that of expected sediments outboard of southern Ryukyu arc. Identical Tl, Sr, Nd and Pb isotope variations are found when comparing arc and back arc lavas, which indicates that sediments fluxes also account for the Tl isotopic variations in the Okinawa Trough lavas. Two-end-member mixing models of Tl with Pb, Sr and Nd isotopes require sediment inputs of $<$ 1%, 0.1–1% and 0.3–2% by weight to the depleted mantle source to account for all these isotopic compositions of lavas from northern, central and southern portion of the Ryukyu arc and Okinawa Trough. Bulk mixing between mantle and sediment end members predict very similar sediment fluxes when using Tl, Sr, Nd and Pb isotopes, which indicates that fractionation of these elements must have happened after mixing between mantle and sediments. This conclusion is corroborated by model calculations of mixing between sediment melts with fractionated Sr/Nd ratios and mantle wedge, which show that no arc lava plot on such mixing lines. Thus bulk sediment mixing, rather than sediment melt, is required for the generation of the lavas from the Ryukyu arc and Okinawa Trough. The requirement of bulk sediment mixing occurring before trace element fractionation in the sub-arc mantle is consistent with models where mélange layers form at the top of the slab and are the principle source material for arc lavas. In addition, the fact that sediment components observed in the Ryukyu arc and Okinawa

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http://dx.doi.org/10.1016/j.gca.2017.08.035

0016-7037/

Trough lavas are similar, suggests that transport of mélange material to the source regions of the arc and back arc is equally efficient. This feature is most readily explained if mélange material is transported from the slab as diapirs.

Keywords: Ryukyu arc; Okinawa Trough; Thallium isotope; Subduction; Sediment

1. INTRODUCTION

Subduction zones are the primary locations of chemical exchange and mass transfer between crust and mantle. It is important to quantify fluxes through subduction zones for understanding the physical and chemical mechanisms that control crustal cycling because these have implications for the thermal structure of subduction zones, volatile addition to the crust and atmosphere, as well as Earth's heat budget. Volcanic rocks from arc-back arc systems are derived from two principal components: the sub-arc mantle wedge and the subducting slab. Materials in the subducting slab comprise primarily sediments and hydrothermally altered oceanic crust (AOC). The physical transfer mechanisms of slab material to the mantle wedge are debated and include sediment melts (Shimoda et al., 1998; Bindeman et al., 2005; Duggen et al., 2007; Spandler and Pirard, 2013), fluids from metamorphic dehydration reactions of both AOC and serpentinized lithospheric mantle (Peacock, 1990; Ulmer and Trommsdorff, 1995; Kendrick et al., 2014; Harvey et al., 2014; Scambelluri et al., 2015), sediment diapirs (Behn et al., 2011) or bulk transfer of mixed slab material (called mélange) as melts or diapirs into the mantle wedge (Marschall and Schumacher, 2012; Nielsen and Marschall, 2017).

In order to track the various components included in arc lavas previous studies have primarily utilized trace element and radiogenic isotopic ratios, which have proven to be powerful tracers of sediment and AOC addition to the mantle wedge (Jakes and Gill, 1970; Kay et al., 1978; McCulloch and Perfit, 1981; Hickey et al., 1986; Plank and Langmuir, 1998; Plank, 2005; Marske et al., 2010). However, these parameters are also subject to ambiguity in terms of the physical mechanism(s) that are responsible for transferring slab material into the mantle wedge (Nielsen et al., 2016; Nielsen and Marschall, 2017). These ambiguities arise because trace element fractionation may occur due to retention of some trace elements in accessory minerals during melting and dehydration of slab components (Johnson and Plank, 1999; Kessel et al., 2005; Hermann and Rubatto, 2009; Skora and Blundy, 2010) and/or isotopic overlap between the mantle wedge and subducted materials (Thirlwall et al., 1996; Taylor and Nesbitt, 1998; Prytulak et al., 2013; Li et al., 2014; Kendrick et al., 2015).

In contrast, some stable isotope tracers provide an appealing complementary approach for the detection and quantification of discrete slab components because significant stable isotope fractionation primarily occurs at relatively low temperatures (Bigeleisen and Mayer, 1947; Blanchard et al., 2017; Teng et al., 2017), prevalent during sediment deposition and hydrothermal ocean crust alteration. Hence, stable isotope signatures imparted onto subducted material can potentially be traced with stable isotope systems as long as the amount of slab material added to the mantle wedge is sufficient to change the isotopic composition of the mixture between slab and mantle wedge. One of the most promising stable isotope systems in tracing slab inputs in arc lavas is that of the element thallium (Tl).

Thallium isotopes can be used to quantify fluxes from the slab because pelagic sediments are highly enriched in Tl and display isotopic compositions that are heavier than the isotopically homogeneous upper mantle (Rehkämper et al., 2004; Nielsen and Rehkämper, 2011; Prytulak et al., 2013). Oceanic crust altered by hydrothermal fluids at low temperatures (<100 °C), on the other hand, display light Tl isotope compositions coupled with high Tl concentrations (Nielsen et al., 2006b; Coggon et al., 2014). Due to the large concentration and isotopic contrast between sediments, AOC and the mantle wedge, Tl isotope ratios were shown to trace pelagic sediment inputs to the Aleutian and Tonga-Kermadec arcs (Nielsen et al., 2016, 2017) that varied systematically along the length of the arc.

Here, we extend the application of Tl isotopes in tracking subducted slab components in arc lavas with a detailed investigation of the Ryukyu arc-back-arc subduction system; the Southern extension of Japan. Sediments are known to subduct underneath the Ryukyu arc and along-arc geochemical variation from the northern to central portion of the Ryukyu arc has been interpreted to reflect increasing involvement of a sedimentary component (Shinjo et al., 2000), but the exact sediment fluxes from the slab have not been determined, primarily because the chemical and isotopic composition of sediments subducting underneath the Ryukyu arc have not been investigated in detail. Subducted components may also be incorporated into lavas in the Okinawa Trough, which is a back-arc basin located behind the Ryukyu arc (Shinjo et al., 1999; Shinjo, 1999). But subducted sediments and/or AOC have been difficult to distinguish due to the uncertainties of trace element and radiogenic isotope compositions of the different components (Shinjo et al., 1999; Shinjo, 1999). With this study, we perform the first comprehensive study of Tl isotope ratios in an arc-back arc system in order to trace sediment and AOC cycling from the volcanic front to the back arc.

2. THALLIUM BACKGROUND IN THE SUBDUCTION ZONES

Thallium (Tl) is a highly incompatible trace element and often grouped with the alkali metals K, Rb, and Cs due to their similar ionic radii and charge (Shaw, 1952; Shannon, 1976; Heinrichs et al., 1980). This affinity causes Tl to be