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Hf–Nd isotope and trace element constraints on subduction inputs at island arcs: Limitations of Hf anomalies as sediment input indicators

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ABSTRACT

New Nd–Hf isotope and trace element data for Javanese volcanoes are combined with recently published data to place constraints on subduction inputs at the Sunda arc in Indonesia and assess the value of Hf anomalies (expressed as Hf/Hf* and Sm/Hf ratios) as tracers of such inputs. Hf anomaly does not correlate with Hf isotope ratio in Javanese lavas, however, Hf/Hf* and Sm/Hf ratios do correlate with SiO_2. Contrary to previous work, we show that Hf anomaly variation may be controlled by fractionation of clinopyroxene and/or amphibole during magmatic differentiation and does not represent the magnitude or type of subduction input in some arcs. Correlation of Sm/Hf with indices of differentiation for other arcs (e.g., Vanuatu, New Britain, and Mariana) suggests that differentiation control on Sm/Hf ratios in volcanic arc rocks may be a relatively common phenomenon. This study corroborates the use of Nd–Hf isotope co-variations in arc volcanic rocks to ascertain subduction input characteristics. The trajectories of regional volcano groups (East, Central and West Java) in Nd–Hf isotope space reveal heterogeneity in the subducted sediment input along Java, which reflects present-day spatial variations in sediment compositions on the down-going plate in the Java Trench. The high Sm/Hf ratio required in the sediment end-member for some Javanese basalts suggests that partial melting of subducted sediment occurs in the presence of residual zircon, and is inconsistent with residual monazite or allanite.

1. Introduction

Ascertaining inputs to the mantle wedge in subduction zones is crucial if we are to understand crustal recycling, constrain the geochemical evolution of mantle reservoirs and investigate the fate of subducted sediments. Using the appropriate geochemical tools to ascertain such inputs (slab fluid and/or melt) is therefore of the utmost importance. Several workers have shown that Hf isotope ratios provide great potential to document mantle source compositions and subducted sediment inputs at island arcs (e.g., Pearce et al., 1999; White and Patchett, 1984; Woodhead et al., 2001). Hf, as a high field strength element (HFSE), is thought to behave conservatively, i.e. to have low solubility in aqueous fluids (cf. Woodhead et al., 2001) and should therefore largely avoid transportation to the mantle wedge during dehydration of subducted sediment or crust. Experimental investigations (Brenan et al., 1995; Kessel et al., 2005; Tatsumi et al., 1986; You et al., 1996) and conclusions from other arc studies (McCulloch and Gamble, 1991; Münker et al., 2004; Pearce and Peate, 1995; Turner et al., 2009) suggest that both Nd and Hf are relatively fluid immobile elements (e.g., compared to Sr). Although limited Hf isotope data is available for altered oceanic crust (AOC) to test the immobility of these elements, recent work by Chauvel et al. (2009) has shown that altered basalts from the western Pacific are indistinguishable in their Hf–Nd isotopic ratio compared to unaltered Pacific MORB. This confirms previous suggestions (e.g., White and Patchett, 1984) that hydrothermal alteration has little or no effect on these ratios (cf. Sr isotopes; Staudigel et al., 1995) and, importantly, then affords the opportunity to constrain sedimentary subduction input additions at island arcs.

Hf concentration anomalies of erupted lavas have also been promoted as a tracer of subducted sediment input (e.g., Marini et al., 2005; Pearce et al., 1999; Tollstrup and Gill, 2005). The Hf anomaly is most commonly defined as the relative depletion/enrichment of Hf compared to Nd and Sm on an extended chondrite-normalised rare earth element (REE) diagram (e.g., Pearce et al., 1999). Therefore, the Sm/Hf ratio is suggested by some as the simplest way of quantifying Hf anomalies in arc lavas (Marini et al., 2005; Pearce et al., 1999). Using Sm/Hf ratios also enables direct comparison between data sets, avoiding variations produced in Hf anomaly values due to the choice of different normalising factors, e.g., C1 chondrite, depleted mantle MORB (DMM) and primitive mantle (PM). Pearce et al. (1999)

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calculate Hf anomalies based on Yb-normalised Hf and Nd element ratios to minimise the effects of partial melting and fractional crystallisation However, the authors indicate that normalisation by Yb is unsuitable if amphibole crystallisation is involved in petrogenesis. As amphibole is thought to be important in the formation of many arc lavas (e.g., Davidson et al., 2007; Foden and Green, 1992) calculation of Hf anomalies using this method may not be appropriate. Negative Hf anomalies are common in arc lavas, and are interpreted as addition of a subduction component with a high Nd/Hf ratio (Pearce et al., 1999). However, the addition of a sediment component with a low Nd/Hf ratio cannot adequately explain the positive Hf anomalies Pearce et al. (1999) observe in the Izu-Bonin-Mariana Protoarc lavas. In contrast, Salters and Hart (1991) suggested that HFSE variations in arc lavas are not solely due to the addition of a slab-derived component and attribute HFSE depletions to a HFSE-depleted sub-arc mantle reservoir.

Consequently, further research is required to ascertain the use of Hf anomalies as source input indicators. Using new, and recently published (e.g., Handley et al., 2007, 2008a, 2010) Nd–Hf isotope and trace element data from Java, this paper investigates the dominant control on Hf anomaly variation and constrains subducted sediment contributions in Javanese arc lavas. Variations in sediment composition deposited on the down-going plate along the Java Trench provide an ideal location to test whether the heterogeneous nature of sediments in the trench can be tracked in the output of the volcanoes. Identifying whether a homogeneous (as proposed by Edwards et al., 1993) or heterogeneous subduction component is involved in petrogenesis will also help to elucidate the nature of the subduction component at the Sunda arc. Our results emphasise that much greater care needs to be taken, when choosing trace element ratios to determine source component characteristics, by prior consideration of the potential influence of magmatic differentiation processes.

2. Geological setting and sample selection

The island of Java is located in the central section of the Sunda arc, which extends from the Andaman Islands north of Sumatra to Flores in the Banda Sea (Hamilton, 1979; Fig. 1). Present volcanic activity is related to the northward subduction of the Indo-Australian Plate beneath the Eurasian Plate. The tectonic features of the area are described in depth by Hamilton (1979). Recent work highlighting the structural complexity of the Java crust is detailed in Smyth et al. (2007) and Clements et al. (2009).

Across-arc changes in chemistry are recognised at the Sunda arc (Edwards, 1990; Hutchinson, 1976; Rittman, 1953; Whitford and Nicholls, 1976), therefore, the rear-arc volcanoes of Muriah (370 km above the Wadati–Benioff zone (WBZ) in Central Java) and Ringgit Beser (210 km above the WBZ in East Java) are excluded from data

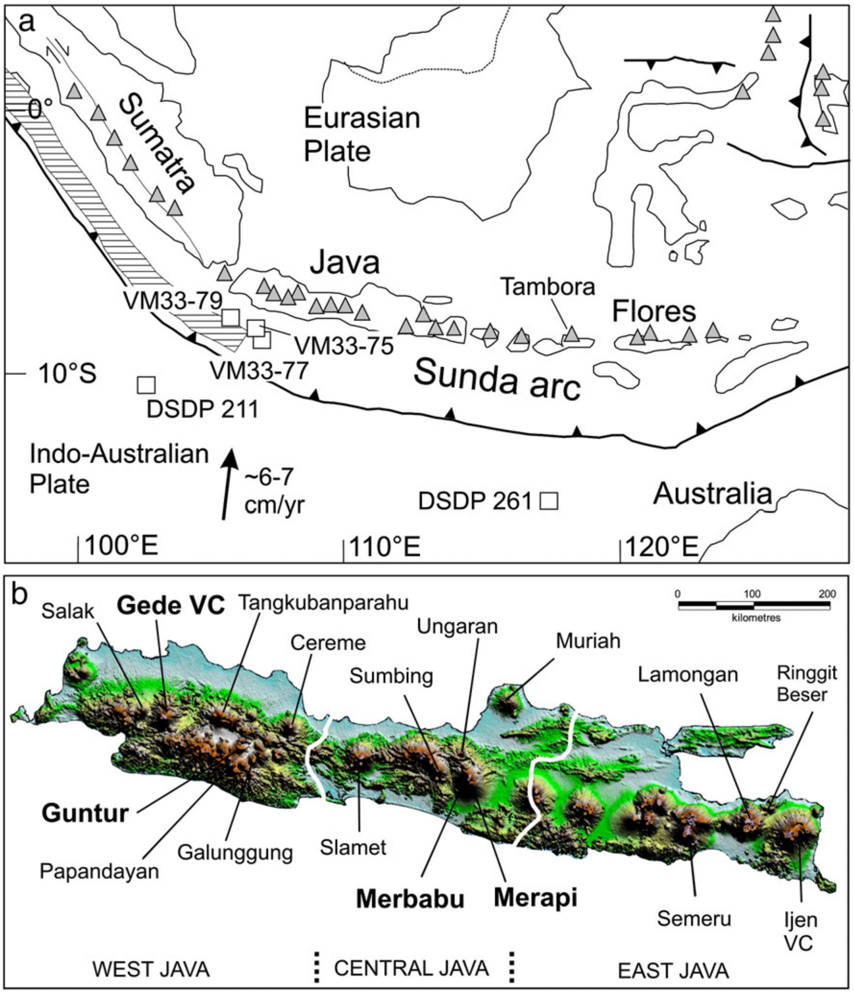

Fig. 1. a) Schematic illustration of the tectonic features of the Sunda arc. Open squares indicate the location of Indian Ocean sediment drill and dredge sites (taken from Gasparon and Varne (1998) and Vroon (1992)). The suggested southeast limit of terrigenous turbidite deposits in the trench is also shown (Hamilton, 1979). b) Map of Java showing volcano locations. The volcanoes for which new geochemical and isotopic data are presented in this study (Gede Volcanic Complex, Guntur, Merapi and Merbabu) are shown in bold. Krakatau is not shown (immediately west of West Java). The two white lines in north–south orientation indicate the geographical boundaries of West, Central and East Java. The Digital Elevation Model of Java is compiled from SRTM data (Shuttle Radar Topography Mission, NASA data).