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Timescales of magma ascent and degassing and the role of crustal assimilation at Merapi volcano (2006–2010), Indonesia: Constraints from uranium-series and radiogenic isotopic compositions

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Abstract

We present new ^{238}U-^{230}Th-^{226}Ra-^{210}Pb-^{210}Po, $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic data of whole-rock samples and plagioclase separates from volcanic deposits of the 2006 and 2010 eruptions at Merapi volcano, Java, Indonesia. These data are combined with available eruption monitoring, petrographic, mineralogical and Pb isotopic data to assess current theories on the cause of a recent transition from effusive dome-building (2006) to explosive (2010) activity at the volcano, as well as to further investigate the petrogenetic components involved in magma genesis and evolution. Despite the significant difference in eruption style, the 2006 and 2010 volcanic rocks show no significant difference in ($^{238}U/^{232}Th$), ($^{230}Th/^{232}Th$) and ($^{226}Ra/^{230}Th$) activity ratios, with all samples displaying U and Ra excesses. The ^{226}Ra and ^{210}Pb excesses observed in plagioclase separates from the 2006 and 2010 eruptions indicate that a proportion of the plagioclase grew within the decades preceding eruption. The 2006 and 2010 samples were depleted in ^{210}Po relative to ^{210}Pb ($(^{210}Po/^{210}Pb)_i < 1$) at the time of eruption but were variably degassed (69%–100%), with the degree of ^{210}Pb degassing strongly related to sample texture and eruption phase. In good agreement with several activity monitoring parameters, ^{210}Po ingrowth calculations suggest that initial intrusion into the shallow magma plumbing system occurred several weeks to a few months prior to the initial 2010 eruption. The 2006 and 2010 samples show a wide range in ($^{210}Pb/^{226}Ra$) activity ratio within a single eruption at Merapi and are largely characterised by ^{210}Pb deficits ($(^{210}Pb/^{226}Ra) < 1$). Assuming a model of complete radon degassing, the ^{210}Pb deficits in the 2006 volcanic rocks indicate relatively longer degassing timescales of ~2–4 years than those given by the 2010 samples of ~0–3 years. The uranium-series and radiogenic isotopic data do not support greater crustal assimilation of carbonate material as the explanation for the more explosive behaviour of Merapi in 2010 (as has been previously suggested) and instead indicate that relatively rapid ascent of a more undegassed magma was the primary difference responsible for the transition in explosive behaviour. This interpretation is in good agreement with gas monitoring data, previous petrological studies (mineral, microlite and melt

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inclusion work) and maximum calculated timescale estimates using Fe-Mg compositional gradients in clinopyroxene, that also suggest more rapid movement of relatively undegassed magma in 2010 relative to 2006.

Keywords: Differentiation; Explosive; Petrogenesis; Subduction zone; ^{238}U-^{230}Th-^{226}Ra-^{210}Pb-^{210}Po; Sr-Nd-Pb isotopes

1. INTRODUCTION

Many volcanoes undergo relatively rapid changes in eruption explosivity, often exhibiting transitions between effusive and explosive behaviour both within and between eruptions, such as at Soufrière Hills Volcano, Lesser Antilles (e.g., Edmonds and Herd, 2007), Novarupta, Alaska (e.g., Nguyen et al., 2014) Kelut, Indonesia (e.g., Jeffery et al., 2013) and Volcán de Colima, Mexico (e.g., Zobin et al., 2015). Therefore, understanding the drivers of such change is of great importance for volcanic hazard mitigation.

Merapi volcano, located 25 km north of Yogyakarta in Central Java in the Sunda arc, is one of the most active volcanoes in Indonesia. The 2010 explosive eruption was the volcano's largest eruption since 1872, resulted in the highest number of fatalities since the 1930 eruption and was much more violent than expected. Prior to the 2010 eruption, recent volcanic activity at Merapi was characterised by the growth and collapse of lava domes (e.g., Andreastuti et al., 2000; Camus et al., 2000; Newhall et al., 2000; Voight et al., 2000; Gertisser and Keller, 2003b; Gertisser et al., 2012), for example, as witnessed in 2006 (Charbonnier and Gertisser, 2008, 2011; Preece et al., 2013; Ratdomopurbo et al., 2013). Whether eruptions at Merapi are effusive or explosive in character is thought to result from a number of factors, such as variations in magma supply from depth, magma ascent rate, magma degassing behaviour and the assimilation of crustal carbonates (Newhall et al., 2000; Gertisser and Keller, 2003a; Chadwick et al., 2007; Deegan et al., 2010; Surono et al., 2012; Troll et al., 2012, 2013; Borisova et al., 2013, 2016; Costa et al., 2013; Preece et al., 2013, 2014, 2016). Petrologic and monitoring data suggest the rapid ascent of a significantly larger, volatile-rich (i.e. relatively undegassed) magma body, and its possible interaction with crustal carbonates, caused the significant change in explosive behaviour of the volcano between 2006 and 2010 (Surono et al., 2012; Borisova et al., 2013; Costa et al., 2013; Preece et al., 2013, 2014, 2016; Erdmann et al., 2016).

The uranium-series (U-series) nuclides provide unique timescale information on magmatic processes ranging from melt production, differentiation and ascent to magmatic degassing prior to eruption (e.g., Bennett et al., 1982; Gill and Williams, 1990; Turner et al., 2000; Condomines et al., 2003; Peate and Hawkesworth, 2005; Bourdon et al., 2006; Reagan et al., 2006; Handley et al., 2008; Reagan et al., 2008; Berlo and Turner, 2010; Sims et al., 2013; Bragagnia et al., 2014) as the nuclides have varied geochemical properties that cause them to be fractionated in distinct ways by different magmatic processes (see Peate and Hawkesworth (2005) for a review). At secular equilibrium the activities of the nuclides (denoted by parentheses) are equal, for example, $(^{230}Th/^{238}U) = 1$. If the decay chain is affected by chemical fractionation of a parent/daughter elemental ratio, restoration of equilibrium by radioactive decay is determined by the half-life of the daughter nuclide involved. Excess ^{238}U ($(^{238}U/^{230}Th) > 1$) and ^{226}Ra ($(^{226}Ra/^{230}Th) > 1$) in subduction zone volcanic rocks are typically attributed to fluid addition from the subduction slab on timescales of less than ~380,000 years and less than ~8000 years, respectively (e.g., Condomines et al., 1988; Gill and Williams, 1990; Hawkesworth et al., 1997) although there may be some modification of ratios by crustal-level processes (e.g., Handley et al., 2008; Reubi et al., 2014; Huang et al., 2016). At magmatic temperatures, ^{234}U is not expected to be fractionated from ^{238}U, and so fresh igneous rocks should have $(^{234}U/^{238}U) = 1$.

Detailed studies of the shorter-lived U-series nuclides from individual volcanic centres, for example, ^{210}Po (half-life = 138.4 days) and its 'grandparent' ^{210}Pb (half-life = 22.6 years), require the collection of young, fresh and dated samples that need to be analysed within a short timeframe after eruption. Polonium partitions efficiently into exsolving volatile phases and is almost completely lost during eruption (Bennett et al., 1982; Gill et al., 1985; Rubin and Macdougall, 1989; Reagan et al., 2008), which results in $(^{210}Po/^{210}Pb) << 1.0$ in erupted lavas. The short-lived ^{210}Pb nuclide is produced by decay of the gas ^{222}Rn (half-life = 3.8 days), which readily enters the volatile phase in magmas (Lambert et al., 1985; Gill et al., 1985). Persistent loss or gain of ^{222}Rn via magmatic degassing or volatile accumulation will therefore create disequilibrium between the nuclides situated before and after ^{222}Rn, that is between the parent ^{226}Ra and the daughter ^{210}Pb. As a result, in an open, degassing system where ^{222}Rn is efficiently lost in the gas phase, deficits of ^{210}Pb are expected, i.e. $(^{210}Pb/^{226}Ra) < 1$. Thus, ^{210}Pb deficits can constrain the duration of degassing (e.g., Gauthier and Condomines, 1999). Alternatively, if gas is supplied from underlying fresh (and probably more mafic) magma, it is possible to create a ^{210}Pb excess (e.g., Kayzar et al., 2009; Condomines et al., 2010).

Previous ^{210}Pb-^{226}Ra disequilibria measurements on Merapi volcanic rocks erupted between 1981 and 1995 showed variable initial $(^{210}Pb/^{226}Ra)$ ratios, from 0.75 to 1 (Gauthier and Condomines, 1999). Based on these data, a <10-year cycle of closed-system magmatic evolution with open degassing followed by episodes of undegassed magmatic recharge was proposed for Merapi (Gauthier and Condomines, 1999). In a study of (^{210}Pb), (^{210}Bi), and (^{210}Po) activities and SO_2 in Merapi gaseous emissions conducted between 1978 and 1995, it was found that growing dome magma had been completely degassed when it reached the surface. It was also suggested that the