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Oxygen isotope heterogeneity of arc magma recorded in plagioclase from the 2010 Merapi eruption (Central Java, Indonesia)

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Abstract

Chemical and isotopic compositions of magmatic crystals provide important information to distinguish between deep juvenile and crustal contributions. In this work, high-resolution multicollector secondary ion mass spectrometry data reveal strong variations of $\delta^{18}O$ values in three plagioclase crystals (800–1700 μm) from two representative basaltic andesite samples of the 2010 Merapi eruption (Central Java, Indonesia). The $\delta^{18}O$ values (from 4.6‰ to 7.9‰) are interpreted to reflect oxygen isotope heterogeneity in the melt composition during plagioclase growth. The lowest $\delta^{18}O$ values (4.6–6.6‰) are found in anorthite-rich cores ($An_{82–97}$), whereas higher $\delta^{18}O$ values (5.7–7.9‰) are found in anorthite-poorer zones ($An_{33–86}$), typically in crystal rims. Combining these new plagioclase $\delta^{18}O$ data with $\delta^{18}O$ of calc-silicate crustal xenoliths erupted between 1994 and 1998, the composition of glass inclusions hosted by the anorthite-rich plagioclase ($An_{82–92}$), available experimental data, and the results of thermodynamic modeling using the Magma Chamber Simulator code, we conclude that the abundant anorthite-rich cores crystallized from a mantle-derived hydrous basaltic to basaltic trachyandesite melt that recharged a deeper (200–600 MPa) magma storage zone, whereas lower anorthite zones crystallized at shallower levels (100–200 MPa). The oxygen isotope variations in the plagioclase are explained by a two-stage model of interaction of the hydrous, mafic mantle-derived magma (1) with old crustal rocks depleted in ^{18}O due to high temperature alteration that yielded the low $\delta^{18}O$ values in the anorthite-rich cores at deep levels (13–20 km), and later (2) with ^{18}O-enriched carbonate material that yielded the high $\delta^{18}O$ values in anorthite-poorer zones at shallow levels (~4.5–9 km). Thermodynamic modeling is consistent with ~18 wt.% assimilation of crustal calc-silicate material at 925–950 °C and 100–200 MPa by the 2010 Merapi basaltic andesite magma prior to eruption. Timescales for plagioclase phenocryst growth and residence in the magmatic plumbing system are

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⩽34 years. The combined data thus reveal efficient magma recharge and crustal assimilation processes that characterize the open-system magma storage and transport systems associated with the 2010 Merapi eruption.

Keywords: Merapi; Plagioclase crystals; Oxygen isotopes; Calc-silicate xenoliths; Crustal assimilation; Timescale

1. INTRODUCTION

One of the major challenges in understanding arc magmatism is to identify and quantify the components that lead to the observed geochemical diversity. This information is fundamental for creating global mass transfer models and for assessing the mass of Earth materials that are fed into the mantle *via* subduction zones. Identifying source components of the near-primary, least fractionated, mafic magmas is not a simple task; moreover, such magmas are rarely erupted in convergent margin settings. More often, one has to study magmas of intermediate composition and thus to account for the added complexity of crustal magma processes, such as fractional crystallization, open-system degassing, crustal assimilation and magma mixing. Erupted lavas, which are typically aggregated at pre-eruptive conditions (e.g., Bindeman et al., 2005; Reubi and Blundy, 2009), commonly represent mixtures of crystals and melts that may have different evolutionary histories and/or sources. Investigating chemical (both elemental and isotopic) zoning in representative crystals of magmatic products is thus a viable way to augment our understanding of the variety of components that contribute to arc magma signatures (e.g., Davidson et al., 2007).

Plagioclase is a very common mineral in the Earth's crust and extraterrestrial materials (Taylor and McLennan, 1985; Brearley and Jones, 1998; Papike et al., 1998; Lange et al., 2013). Its calcic end-member, anorthite, is frequently found in cores of crystals in igneous inclusions and crustal xenoliths, and is particularly abundant in arc-related magmatic rocks (e.g., Bindeman and Bailey, 1999; Pichavant et al., 2002; Martel et al., 2006; Chadwick et al., 2007; Plechov et al., 2008; Deegan et al., 2010; Borisova et al., 2013; Troll et al., 2013), thereby implying their importance in unravelling the early history of the subduction-related magmas. Indeed, starting from its primary source, magma constantly interacts with surrounding solid material as well as other magmas. To constrain the composition of magmatic sources and additional crustal components, it is important to document the chemical and isotopic exchange mechanisms that control magma genesis. For arc magmas, interacting with carbonate crust, as seen at Merapi, the mechanisms of the crustal assimilation may be deciphered from natural samples and through experiments (Freda et al., 2008; Gaeta et al., 2009; Iacono-Marziano et al., 2008, 2009; Deegan et al., 2010; Mollo et al., 2010; Borisova et al., 2013; Jolis et al., 2013). Recent advances in *in situ* microanalytical methods (e.g., Davidson et al., 2007), thermodynamic and geochemical modeling (Zhang and Cherniak, 2010; Bohrson et al., 2014), and experimental approaches at high pressure–temperature conditions (e.g., Deegan et al., 2010; Jolis et al., 2013) make it now possible to develop novel petrogenetic models and constrain such magma–crust interaction processes and their timescales in more detail.

To test these "process-signal" relationships, we have chosen Merapi volcano (Central Java, Indonesia) due to its detailed record of crustal processes in the igneous products. Using an integrated approach, we examine here the role of both magma–crust and magma–magma interactions in the 2010 eruption of Merapi, Indonesia. In particular, *in situ* microanalytical methods often reveal larger variations of isotope ratios at a micrometer scale, as compared to the grain- and rock-scales (e.g., Chadwick et al., 2007; Davidson et al., 2007; Borisova et al., 2014; Winpenny and Maclennan, 2014); these observations prompted us to further explore isotopic and elemental information from Merapi volcano. We obtained this information from the most abundant crystalline phase, plagioclase, in the 2010 Merapi eruptive products, by employing *in situ* oxygen isotope composition determined using multicollector secondary ion mass spectrometry (SIMS). Three representative Merapi 2010 plagioclase crystals reveal considerable intra-crystal isotopic heterogeneity. Additionally, we compare these new *in situ* plagioclase data with new grain-scale oxygen isotope analyses of several mineral fractions from representative calc-silicate xenoliths that are frequently observed in the recent Merapi volcanic products. Finally, to more fully constrain the petrogenetic processes that produced the 2010 Merapi plagioclases, we performed thermodynamic modeling utilizing the new the Magma Chamber Simulator code (Bohrson et al., 2014) and anorthite-rich plagioclase-hosted melt inclusions.

2. GEOLOGICAL BACKGROUND

Merapi stratovolcano is located 25–30 km north of the city of Yogyakarta, Indonesia (Fig. 1). The volcano is composed mainly of basaltic-andesite tephra, pyroclastic flows, lava, and lahar deposits. Since the 19th century, Merapi has erupted every 4–6 years, with most of these eruptions having explosivity indices ⩽VEI 2, although moderate VEI 3 (1832, 1849, 1930, 1961) to large VEI 4 (1822, 1872) eruptions have also occurred (Costa et al., 2013). However, in late October and early November of 2010, Merapi changed its eruptive style, producing its most powerful, explosive and voluminous eruption in the last 100 years. This eruption likely marked a change in Merapi's activity towards more explosive behavior (Surono et al., 2012).

Numerous methods (melt inclusion study, *in situ* mineral and glass chemistry analyses, ash leaching, bulk rock analyses and geochemical modeling) have been applied to constrain composition of the 2010 pre-eruptive melts and bulk syn-eruptive fluid (Borisova et al., 2013; Costa et al., 2013;