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Earthquake induced variations in extrusion rate: A numerical modeling approach to the 2006 eruption of Merapi Volcano (Indonesia)

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ABSTRACT

Extrusion rates during lava dome-building eruptions are variable and eruption sequences at these volcanoes generally have multiple phases. Merapi Volcano, Java, Indonesia, exemplifies this common style of activity. Merapi is one of Indonesia's most active volcanoes and during the 20th and early 21st centuries effusive activity has been characterized by long periods of very slow (<0.1 m^3 s^{-1}) extrusion rate interrupted every few years by short episodes of elevated extrusion rates (1–4 m^3 s^{-1}) lasting weeks to months. One such event occurred in May–July 2006, and previous research has identified multiple phases with different extrusion rates and styles of activity. Using input values established in the literature, we apply a 1D, isothermal, steady-state numerical model of magma ascent in a volcanic conduit to explain the variations and gain insight into corresponding conduit processes. The peak phase of the 2006 eruption occurred in the two weeks following the May 27 M_w 6.4 earthquake 50 km to the south. Previous work has suggested that the peak extrusion rates observed in early June were triggered by the earthquake through either dynamic stress-induced overpressure or the addition of CO_2 due to decarbonation and gas escape from new fractures in the bedrock. We use the numerical model to test the feasibility of these proposed hypotheses and show that, in order to explain the observed change in extrusion rate, an increase of approximately 5–7 MPa in magma storage zone overpressure is required. We also find that the addition of $\sim$1000 ppm CO_2 to some portion of the magma in the storage zone following the earthquake reduces water solubility such that gas exsolution is sufficient to generate the required overpressure. Thus, the proposed mechanism of CO_2 addition is a viable explanation for the peak phase of the Merapi 2006 eruption. A time-series of extrusion rate shows a sudden increase three days following the earthquake. We explain this three-day delay by the combined time required for the effects of the earthquake and corresponding CO_2 increase to develop in the magma storage system (1–2 days), and the time we calculate for the affected magma to ascend from storage zone to surface (40 h). The increased extrusion rate was sustained for 2–7 days before dissipating and returning to pre-earthquake levels. During this phase, we estimate that 3.5 million m^3 DRE of magma was erupted along with 11 ktons of CO_2. The final phase of the 2006 eruption was characterized by highly variable extrusion rates. We demonstrate that those changes were likely controlled by failure of the edifice that had been confining the dome to Merapi's crater and subsequent large dome collapses. The corresponding reductions in confining pressure caused increased extrusion rates that rapidly rebuilt the dome and led to further collapses, a feedback cycle that prolonged the eruption. In a more general sense, this study demonstrates that both internal changes, such as magma volatile content and overpressure, and external forces, such as edifice collapse and regional earthquakes, can affect variations in eruption intensity. Further, we also demonstrate how these external forces can initiate internal changes and how these parameters may interact with one another in a feedback scenario.

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1. Introduction

Volcanic eruptions forming lava domes present a prolonged and dangerous hazard to surrounding populations. The primary hazard of these eruptions is pyroclastic density currents (PDCs) caused by collapse of an active lava dome at the summit (e.g., Voight et al., 2000). While the size and frequency of PDCs generally correlates with the extrusion rate (Nakada et al., 1999; Carr et al., 2016), and periods of increased extrusion rate can be anticipated through extensive geodetic and seismic monitoring (e.g. Surono et al., 2012; Ratdomopurbo et al., 2013), the causes of changes in extrusion rate

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are generally not well constrained. Numerical models of magma ascent in volcanic conduits have previously tested the effect of different parameters on extrusion rate, such that general relationships between a range of magma and conduit conditions have been well described (Melnik and Sparks, 1999; Mastin, 2002; de' Michieli Vitturi et al., 2008, 2010). However, these relationships can be applied to determine the cause of varying extrusion rates in real eruptions only when the system is sufficiently well-constrained to reduce the number of free parameters. Numerous eruptions at Merapi Volcano (Java, Indonesia) are well documented, making them excellent case studies to further test the role of magma properties, conduit conditions, and external forces such as earthquakes in controlling volcanic processes. Here we apply a 1D, steady-state conduit model, with inputs well-constrained for the 2006 Merapi eruption, and pair it with a detailed record of extrusion rate (Harris and Ripepe, 2007; Ratdomopurbo et al., 2013; Preece et al., 2013; Carr et al., 2016) to explain the causes of variations during the eruption sequence. We also test the feasibility of hypotheses proposed in previous works (Walter et al., 2007; Harris and Ripepe, 2007; Deegan et al., 2010; Troll et al., 2012) that suggest a regional tectonic earthquake triggered the peak phase of the eruption.

1.1. Merapi's activity

Merapi Volcano, located 30 km north of Yogyakarta in central Java (Fig. 1), is one of Indonesia's most active and dangerous volcanoes. For much of the late 19th, 20th, and early 21st centuries, activity at Merapi Volcano consisted of continued slow extrusion leading to the formation of a series of basaltic-andesite lava domes (Hammer et al., 2000; Voight et al., 2000). The long-term background extrusion rate at Merapi is approximately 0.03 $m^3\,s^{-1}$ (Siswowidjoyo et al., 1995; rates for dense rock equivalent values, DRE = 2800 $kg\,m^{-3}$, Costa et al., 2013). Every few years (an average of <7 yr, Ratdomopurbo et al., 2013) extrusion rates have increased to 1–4 $m^3\,s^{-1}$ for short periods lasting a few weeks to months during which time PDCs have been most common (Siswowidjoyo et al., 1995). This pattern of low-level background activity interrupted by relatively brief periods of increased extrusion rate and PDC frequency was so persistent at Merapi that it has been described as "Merapi-type" activity and the term is used to describe similar eruptions at other volcanoes (Voight et al., 2000).

Observations and studies of the 2006 eruption have identified five phases (Global Volcanism Program, 2007; Harris and Ripepe, 2007; Ratdomopurbo et al., 2013; Preece et al., 2013; Carr et al., 2016). Phase 1 began on April 26 when lava extrusion increased above background levels (Ratdomopurbo et al., 2013), though extrusion rates were ≤ 1 $m^3\,s^{-1}$ (Ratdomopurbo et al., 2013; Carr et al., 2016). Extrusion rate increased to ~ 2 $m^3\,s^{-1}$ during Phase 2, which began on May 11 with the first PDCs generated by dome collapse (Ratdomopurbo et al., 2013; Preece et al., 2013; Carr et al., 2016). The start of Phase 3 is marked by the May 27th M_W 6.4 strike-slip earthquake located at a depth of 10 km approximately 50 km S of the Merapi vent (7.89°S, 110.41°E) (Fig. 1). The earthquake caused thousands of fatalities around Yogyakarta (Nakano et al., 2006). Following the earthquake, the frequency of PDCs increased (Walter et al., 2007) and the average extrusion rate rose to 3.3–3.6 $m^3\,s^{-1}$ for a period of nearly two weeks (Harris and Ripepe, 2007; Ratdomopurbo et al., 2013; Preece et al., 2013; Carr et al., 2016). This increase was followed by a brief decrease in activity during Phase 4 (June 9–13) when extrusion rates returned to ~ 1 $m^3\,s^{-1}$ (Harris and Ripepe, 2007; Carr et al., 2016). The weight of the growing lava dome initiated a progressive failure of the southern crater wall during Phases 3 and 4 (Ratdomopurbo et al., 2013). This failure caused the primary direction of PDCs to switch from the SW down the Krasak and Boyong drainages to

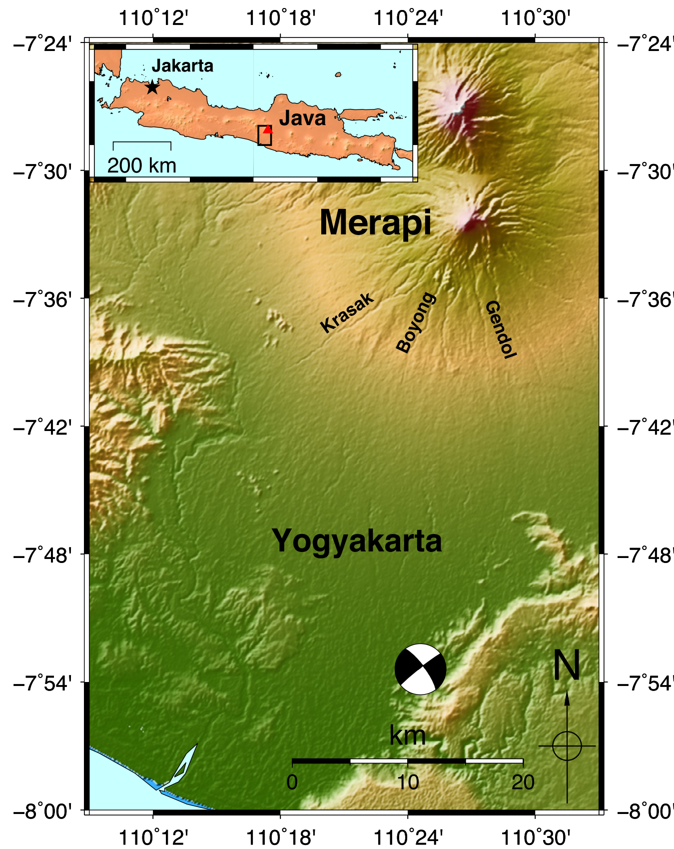

Fig. 1. Location of Merapi Volcano. Merapi Volcano is 30 km north of the city of Yogyakarta and 50 km north of the epicenter of the 2006 earthquake (focal mechanism from the Harvard CMT catalog). Major PDC drainages for the 2006 eruption are labeled. Inset: location of the main figure (box) and Merapi (triangle) on the island of Java.

the S down the Gendol drainage (Charbonnier and Gertisser, 2008; Ratdomopurbo et al., 2013) (Fig. 1). The start of Phase 5 is marked by the final and complete collapse of the crater wall on June 14, leading to the largest PDCs of the 2006 event which traveled up to 7 km from the vent and caused the only two fatalities directly attributed to the eruption (Charbonnier and Gertisser, 2008). Extrusion rates were variable during Phase 5, ranging from 1 to 2 $m^3\,s^{-1}$ (Preece et al., 2013; Carr et al., 2016). Carr et al. (2016) mark the end of Phase 5 on July 10, when the Indonesian Center of Volcanology and Geological Hazards Mitigation lowered the alert level for Merapi from 4 to 3 (on a 1–4 scale) (Global Volcanism Program, 2007).

Previous research has suggested that the peak extrusion rate during Phase 3 is related to the occurrence of the May 27 earthquake (Walter et al., 2007; Harris and Ripepe, 2007; Deegan et al., 2010; Troll et al., 2012). While the static stress change caused by the earthquake ($\sim$3 kPa, Walter et al., 2007) was not sufficient to increase extrusion rate to the observed values, the dynamic stress change caused by passing seismic waves likely played a role (Walter et al., 2007). The effect of dynamic stress change is further supported by Harris and Ripepe (2007), who identify an increase in extrusion rate at both Merapi and Semeru Volcano (280 km to the east) in the days following the earthquake. Both Harris and Ripepe (2007) and Walter et al. (2007) suggest that dynamic stress may cause increased vesiculation and promote bubble growth in the magma which leads to increased pressure and buoyancy in the magma and therefore higher extrusion rates (Manga and Brodsky, 2006).

Deegan et al. (2010) and Troll et al. (2012) propose an alternative explanation for increased activity after the earthquake.

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