Journal of Volcanology and Geothermal Research 311 (2016) 60–71

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

The 2006 lava dome eruption of Merapi Volcano (Indonesia): Detailed analysis using MODIS TIR

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ARTICLE INFO

Article history:
Received 24 June 2015
Accepted 10 December 2015
Available online 24 December 2015

Keywords:
Merapi
Thermal remote sensing
Lava domes
Eruption rate
Pyroclastic density currents

ABSTRACT

Merapi is one of Indonesia's most active and dangerous volcanoes. Prior to the 2010 VEI 4 eruption, activity at Merapi during the 20th century was characterized by the growth and collapse of a series of lava domes. Periods of very slow growth were punctuated by short episodes of increased eruption rates characterized by dome collapse-generated pyroclastic density currents (PDCs). An eruptive event of this type occurred in May–June, 2006. For effusive eruptions such as this, detailed extrusion rate records are important for understanding the processes driving the eruption and the hazards presented by the eruption. We use thermal infrared (TIR) images from the Moderate Resolution Imaging Spectrometer (MODIS) instrument on NASA's Aqua and Terra satellites to estimate extrusion rates at Merapi Volcano during the 2006 eruption using the method of Harris and Ripepe (2007). We compile a set of 75 nighttime MODIS images of the eruptive period to produce a detailed time series of thermal radiance and extrusion rate that reveal multiple phases of the 2006 eruption. These data closely correspond to the published ground-based observational record and improve observation density and detail during the eruption sequence. Furthermore, additional analysis of radiance values for thermal anomalies in Band 21 ($\lambda = 3.959$ μm) of MODIS images results in a new framework for detecting different styles of activity. We successfully discriminate among slow dome growth, rapid dome growth, and PDC-producing dome collapse. We also demonstrate a positive correlation between PDC frequency and extrusion rate, and provide evidence that extrusion rate can increase in response to external events such as dome collapses or tectonic earthquakes. This study represents a new method of documenting volcanic activity that can be applied to other similar volcanic systems.

1. Introduction

Mount Merapi, located in central Java, Indonesia (Fig. 1), is one of Indonesia's most active and dangerous volcanoes. During the 20th century frequent lava dome growth at the summit presented a near-constant threat of pyroclastic density currents (PDCs) to the densely populated area around the mountain. Large-scale evacuations and fatalities associated with these PDCs were common (Voight et al., 2000). This style of activity, an active lava dome producing frequent PDCs, is commonly known as a "Merapi-type" eruption (Voight et al., 2000).

Documenting the extrusion rate of an active lava dome is critical to understanding the hazards presented by Merapi-type eruptions. Increases in extrusion rate have been linked to the risk of dome collapses and PDCs (Nakada et al., 1999; Calder et al., 2002) and is an observable quantity that provides insight into deep and shallow subsurface processes (Melnik and Sparks, 1999, 2002; de' Michieli Vitturi et al., 2008, 2010, 2013). Unfortunately, frequent and accurate extrusion rate measurements can be difficult to obtain, especially at remote volcanoes or observatories with limited resources. However, extrusion rate can be derived from satellite thermal infrared (TIR) images that are acquired daily (Harris et al., 1997). High-resolution satellite TIR images can also be used to extract details about volcanic activity, such as locating regions of active dome growth or identifying the collapsing front of a lava lobe (e.g., Oppenheimer et al., 1993; Wooster et al., 2000). Here we combine previously published ground-based observations from the Merapi eruption in 2006 with numerous satellite TIR images from the same time interval and document the different phases of dome growth and collapse in detail by extracting a daily time series of extrusion rate and distinguishing pure dome growth from PDC-producing collapses. In doing so, we also develop a new framework for distinguishing different styles of activity from satellite observations. These data and the techniques developed in this manuscript provide insight into lava dome hazards and the processes controlling them at Merapi and similar volcanoes around the world.

1.1. Recent Merapi activity

For much of the 20th century, a series of basaltic-andesite (Hammer et al., 2000) lava domes were active at the summit of Merapi. Long

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http://dx.doi.org/10.1016/j.jvolgeores.2015.12.004
0377-0273/

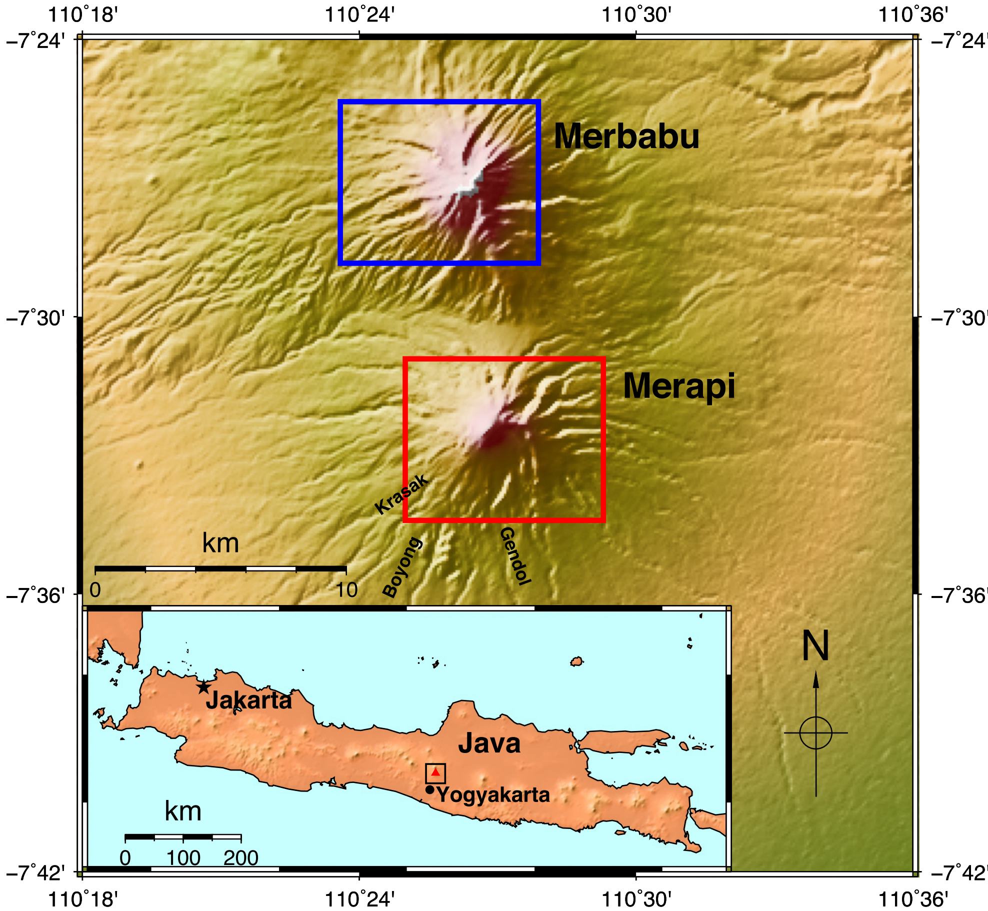

Fig. 1. Location of Merapi Volcano. Merapi and Merbabu Volcanoes, showing the regions of interest (ROIs) that were used for the extrusion rate calculations (red box) and background subtraction (blue box), and the primary PDC drainages for the 2006 eruption (Krasak, Boyong, & Gendol). Inset: location of the main figure (box) and Merapi (triangle) on the island of Java, showing the proximity of Merapi to the city of Yogyakarta.

periods of low-level activity were punctuated by eruptive sequences consisting of elevated extrusion rates and multiple gravitational collapse-generated PDCs. Merapi's 20th century eruptions also occasionally included small explosions, but were rarely classified as larger than VEI 2 (Volcano Explosivity Index; Newhall and Self, 1982). Larger VEI 3 events occurred in 1930-1931 and 1961. Prior to 2010, the most recent periods of elevated extrusion rates and frequent PDCs occurred in 1992, 1994, 1997–1998, 2001, and 2006 (Voight et al., 2000; Ratdomopurbo et al., 2013). The 20th century-averaged eruption rate at Merapi was 0.03 m^3 s^{-1}, while elevated activity associated with Merapi-type events occurred every few years with average eruption rates of 1–4 m^3 s^{-1} (Siswowidjoyo et al., 1995).

The 2006 eruption started with extrusion of lava on or around April 26 (Ratdomopurbo et al., 2013) and began building a new dome (beginning of Phase 1, Table 1). The first PDCs occurred on May 11 (beginning of Phase 2, Table 1). On May 27 (beginning of Phase 3), a M_w 6.4 earthquake occurred about 50 km SSE of Merapi (Walter et al., 2007), which was followed by an increase in extrusion rate and the frequency of PDCs (Harris and Ripepe, 2007; Walter et al., 2007; Ratdomopurbo et al., 2013). The elevated level of activity continued through June 8 (end of Phase 3, Table 1) (Ratdomopurbo et al., 2013), after which the intensity of the eruption decreased (Phase 4, Table 1). During Phase 3, the new lava dome was growing over and applying pressure to the southern wall of the summit crater, causing a transition from PDCs dominantly

Table 1
Extrusion rate and volume for the 2006 eruption of Merapi from multiple sources. Average extrusion rates and volume of magma extruded compare well with previous works based on both remote sensing and ground-based estimates. This is the case for each phase of the eruption and for the entire eruption. BGVP stands for Bulletin of the Global Volcanism Program (2007).

Phase	Dates	Activity	Extrusion rate (m^3/s)				Cumulative volume extruded (10^6 m^3)			
			This Study	Ratdomopurbo et al. (2013)	Harris and Ripepe (2007)	BGVP	This Study	Ratdomopurbo et al. (2013)	Harris and Ripepe (2007)	BGVP
1	April 26–May 10	Initial dome growth	0.2	1			0.2	1.0		
2	May 11–May 26	First pyroclastic flows observed	0.7	1.9	0.54		1.3	2.6	0.5	2.3
3	May 27–June 8	Peak of activity following 5/27 6.4M_w EQ	3.6	3.3	1.27	1.16	4.5	5.3	1.6	4.0
4	June 9–June 13	Significant decrease in activity	0.7		0.94		4.9		2.0	
5	June 14–July 10	Renewed pyroclastic flow activity then decreases until alert level lowered	1.6				8.4			
Total			1.6				8.4	5.3		