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Insights into the October–November 2010 Gunung Merapi eruption (Central Java, Indonesia) from the stratigraphy, volume and characteristics of its pyroclastic deposits

Shane J. Cronin [a,*], Gert Lube [a], Devi S. Dayudi [b], Sri Sumarti [b], S. Subrandiyo [b], Surono [c]

[a] Volcanic Risk Solutions, Institute of Agriculture and Environment, Massey University, Private Bag 11 222, Palmerston North, New Zealand
[b] Balai Penyelidikan dan Pengembangan Tekhnologi Kegunungapian (BPPTK), Jalan Cendana, Yogyakarta 55166, Java, Indonesia
[c] Center of Volcanology and Geologic Hazard Mitigation (CVGHM), Jalan Diponogero, Bandung 40122, Java, Indonesia

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A B S T R A C T

The 2010 eruption of Merapi was the second most deadly in the historic record of this volcano, claiming over 380 lives. By relating the observations of this eruption with detailed examination of deposit distribution, stratigraphy and sedimentology, a reconstruction of the properties of the pyroclastic density currents (PDCs) is presented, including the valley controlled block-and-ash flows (BAFs) and widespread, energetic pyroclastic surges. The distribution, volume and mobility characteristics of all types of PDC during the eruption sequence show evidence for levels of intensity unseen since the large-scale 1872 and 1930 eruption phases, especially during the climactic events of October 26 and November 5. Many tephra falls interbedded with PDC units show that most dome-collapse events occurred along with and between explosive vulcanian eruptions. The 2010 eruption produced very long-runout BAFs, reaching 16.1 km in the Kali Gendol on November 5. This runout could be explained by its large-volume (20 million m^3), around 10 times that of previous Merapi BAFs during the last 130 years. Major avulsion of these dense BAFs to form overbank deposits became more common through the eruptive sequence as the valley was progressively filled with successive PDC deposits. Spreading avulsed BAFs were a particular hazard downstream of ~10 km where the landscape is less dissected. Less clear, however, is why pyroclastic surges extended up to 10 km from the vent on November 5 and >6.4 km on October 26. These expanded much farther from BAF margins (~2 km) than ever seen before at Merapi. In one location they were decoupled from valley-centered BAFs with high momentum, traveling initially laterally across steep valley systems, before draining downslope. At this site, on the western side of the upper Gendol at around 3 km from source, surge decoupling was apparently exacerbated by upstream collision and deflection of high-flux, hot and gas-rich BAFs against the cliffs of Gunung Kendil. The 1.4 km-long cliff face was impacted directly for the first time in 2010 events, and may have been responsible for the formation of larger than normal turbulent ash-rich clouds above BAFs. These results imply that future eruption events under the present summit and upper flow-path configuration are also highly likely to generate wide dispersal pyroclastic surges and extreme hazard, especially now that dense forest has been destroyed on the upper southern slopes of the volcano.

1. Introduction

Many eruptions of Merapi over the last 80 years have generated destructive and deadly pyroclastic density currents (PDCs) in association with lava dome effusion (Boudon et al., 1993; Abdurachman et al., 2000; Andreastuti et al., 2000; Voight et al., 2000; Schwarzkopf et al., 2005; Charbonnier and Gertisser, 2008; Gertisser et al., 2012). The ~18 most destructive of these eruptions and the six that caused fatalities (including those in 2006 and 2010) produced currents that spilled out of channels (Bourdier and Abdurachmann, 2001; Lube et al., 2011). Such currents also occurred in the most lethal event known, on 18–19 December 1930; at least 1369 people were killed by pyroclastic density currents (*nuées ardentes*) (Neumann van Padang, 1933). The volcano has become the type-example for "Merapi-style" block-and-ash flows, engendered by the gravitational collapse of growing lava domes, with the bulk of deposition confined to valleys (Abdurachman et al., 2000). The cases where eruptions have been particularly deadly or destructive, were attributed to: (A) avulsion of the dense basal avalanche part of BAFs (or basal avalanches) from channels due to dynamically thickening flow fronts (Schwarzkopf et al., 2005), or rapid changes in channel confinement and sinuosity (Lube et al., 2011); (B) decoupling of low-density pyroclastic surges from basal avalanches due to high ash contents (possibly amplified during collapses of hot gas-rich domes), as well as high volumetric fluxes in confined valleys (Bourdier

* Corresponding author. Tel.: +64 63569099; fax: +64 63505632.
E-mail addresses: s.j.cronin@massey.ac.nz (S.J. Cronin), g.lube@massey.ac.nz (G. Lube).

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and Abdurachmann, 2001); or (C) surge-generation by sudden hydraulic-jumps, such as at major breaks in slope, or descent of steep cliffs (e.g., Kelfoun et al., 2000; Bourdier and Abdurachmann, 2001; Schwarzkopf et al., 2002). Other mechanisms for generating highly destructive and widespread pyroclastic density currents from similar types of eruptions include directed explosive blasts from gas-pressured

Table 1
Eruption chronology summary based upon records of the Balai Penyelidikan dan Pengembangan Tekhnologi Kegunungapian (BPPTK) in Yogyakarta, and the Center of Volcanology and Geologic Hazard Mitigation (CVGHM) in Bandung.

Date	Dome activity	Eruption columns	Pyroclastic density currents	Remarks
20.10–22.10	2006 dome showing increased incandescence	Small explosions on 21.10	Rockfalls reported on 20.10 and 21.10	Summit inflation since September, increasing HCl and decreasing H_2O gas levels
23.10–25.10	Sharp increase in inflation	Steam and gas emissions		M 7.7 Mentawai earthquake c. 1200 km WNW; 10 km evacuation radius
26.10	Strong incandescence; explosions destroyed old dome	Multiple explosions reaching 1.5 km height starting 17:02; 18 km plume spreading W (VAAC Darwin)	8 seismically detected PDCs in Kali Gendol at: 17:02 (c. 9 min) 17:18 (c. 4 min) 17:23 (c. 5 min) 17:30 (c. 2 min) 17:37 (c. 33 min) 18:16 (c. 5 min) 18:21 (c. 33 min)	3 BAF lobes in Gendol with runouts of 4.95, c. 4.9 and c. 4.8 km seen on photographs taken on 28.10; BAF avulsion into Tlogo valley; mobile surges into Kinahrejo and Kendil areas; at least 35 deaths
28.10	New dome extrusion	Multiple small explosions starting at c. 16:30	3 seismically detected PDCs in Gendol with estimated runouts of 3.5 km	Garuda Airline accident; ash damage to left jet engine
29.10			33 seismically detected PDCs in Gendol with estimated runouts of 2–4 km	
30.10		Multiple explosions; 18 km plume spreading S	2 seismically detected PDCs at: 00:16 (c. 7 min into Lamat, Senowo and Krasak drainages) 00:35 (c. 22 min into Gendol, Kuning, Krasak and Boyong drainages)	Ash fall in Yogyakarta
31.10	New dome growth		4 seismically detected PDCs	
1.11	Dome growth	6.1 km plume (VAAC Darwin)	7 seismically detected PDCs in Kali Gendol with estimated runouts of c.4 km	Aster Image captures thermal signature of new dome, and 6.5–7 km long BAF deposit in Gendol
2.11	Dome growth	6.1 km plume (VAAC Darwin)	26 seismically detected PDCs; estimated runouts to 3.5 km	
3.11	Dome growth and dome destruction; very strong seismicity and explosion signals throughto 5.11		38 seismically detected PDCs: 11:11–13:19 (c. 2 min) 14:00–14:03 (4 c. 1 min PDC/rockfall signals) 14:04–14:27 (series of c. 5 min PDC signals) 14:44 (1.5 h lasting PDC signals)	Reported runout for 14:04–14:27 PDCs was c. 10 km in Gendol; Runout of 14:44 PDCs in Gendol to c. 9 km reported at c. 17:30; 19 other visually confirmed PDCs with reported runouts of c. 4 km
4.11	Dome growth and dome destruction		PDCs into Gendol to c. 9.5 km, and into Bebeng, Putih, Boyong, Senowo and Apu drainages	
5.11	Dome growth and dome destruction	>15 km plume spreading WSW–WNW (NASA Earth Observatory)	Largest explosion (related to main event) starting on 5.11 at 0:05	BAFs in Gendol to 16.1 km; 1st PDC arrival at c. 15.5 km on 5.11 at c. 0:25 (from eye-witness accounts); surges into Kinahrejo and Gendol areas
6.11–7.11	New dome growth	Multiple incandescent explosions and ash plumes reaching heights of c. 7 km on 7.11	Explosions and PDCs into multiple drainages; PDCs increasing in runout on 7.11 and reported to reach c. 5–8 km runouts in Gendol	Main ash dispersal to WNW on 6.11 and to WSW on 7.11
8.11–29.11		Multiple ash plumes reaching 0.8 to 7.6 km heights	Few PDCs gradually decreasing in runout	Lahars occurring in drainages from NNW to SE