Journal of Volcanology and Geothermal Research 241–242 (2012) 121–135

Contents lists available at SciVerse ScienceDirect

Journal of Volcanology and Geothermal Research

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

The 2010 explosive eruption of Java's Merapi volcano—A '100-year' event

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ARTICLE INFO

Article history:
Received 4 September 2011
Accepted 12 June 2012
Available online 21 June 2012

Keywords:
Merapi
Gas emissions
Satellite imagery
Volcano-seismology
Deformation
Petrology
International collaboration

ABSTRACT

Merapi volcano (Indonesia) is one of the most active and hazardous volcanoes in the world. It is known for frequent small to moderate eruptions, pyroclastic flows produced by lava dome collapse, and the large population settled on and around the flanks of the volcano that is at risk. Its usual behavior for the last decades abruptly changed in late October and early November 2010, when the volcano produced its largest and most explosive eruptions in more than a century, displacing at least a third of a million people, and claiming nearly 400 lives. Despite the challenges involved in forecasting this 'hundred year eruption', we show that the magnitude of precursory signals (seismicity, ground deformation, gas emissions) was proportional to the large size and intensity of the eruption. In addition and for the first time, near-real-time satellite radar imagery played an equal role with seismic, geodetic, and gas observations in monitoring eruptive activity during a major volcanic crisis. The Indonesian Center of Volcanology and Geological Hazard Mitigation (CVGHM) issued timely forecasts of the magnitude of the eruption phases, saving 10,000–20,000 lives. In addition to reporting on aspects of the crisis management, we report the first synthesis of scientific observations of the eruption. Our monitoring and petrologic data show that the 2010 eruption was fed by rapid ascent of magma from depths ranging from 5 to 30 km. Magma reached the surface with variable gas content resulting

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0377-0273/$ – see front matter
doi:10.1016/j.jvolgeores.2012.06.018

in alternating explosive and rapid effusive eruptions, and released a total of ~0.44 Tg of SO_2. The eruptive behavior seems also related to the seismicity along a tectonic fault more than 40 km from the volcano, highlighting both the complex stress pattern of the Merapi region of Java and the role of magmatic pressurization in activating regional faults. We suggest a dynamic triggering of the main explosions on 3 and 4 November by the passing seismic waves generated by regional earthquakes on these days.

1. Introduction

Merapi stratovolcano is located 25–30 km north of the metropolitan area of Yogyakarta, Indonesia (Fig. 1) and the environs are home to around of 1.6 million people. It overlies the Java subduction zone and is composed mainly of basaltic-andesite tephra, pyroclastic flow, lava, and lahar deposits. Eruptions during the twentieth century typically recurred every 4 to 6 years and produced viscous lava domes that collapsed to form pyroclastic flows and subsequent lahars. These eruptions were relatively small, with typical eruptive volumes of $1–4\times10^6\,m^3$ and magnitudes or volcanic explosivity indices (VEI) of 1–3 (Andreastuti et al., 2000; Camus et al., 2000; Newhall et al., 2000; Voight et al., 2000a), where magnitude (Pyle, 2000) is given by $[M_e = \log_{10}(\text{mass of products in kg}) - 7]$. Merapi volcano has been studied extensively by Indonesian and international teams, leading to improved understanding of the volcano's seismology (Hidayat et al., 2000; Ratdomopurbo and Poupinet, 2000; Sens-Schönfelder and Wegler, 2006), deformation (Beauducel and Cornet, 1999; Voight et al., 2000b; Young et al., 2000), potential field geophysics (Jousset et al., 2000; Zlotnicki et al., 2000; Tiede et al., 2005), gas emissions (Le Guern and Bernard, 1982; Nho et al., 1996; Zimmer and Erzinger, 2003; Humaida et al., 2007; Toutain et al., 2009; Allard et al., 2011), petrology (Gertisser and Keller, 2002, 2003; Chadwick et al., 2007; Deegan et al., 2010, 2011), physical volcanology (Charbonnier and Gertisser, 2008) and lahar inundation (Lavigne et al., 2000). Merapi's high-temperature (400–850 °C) summit fumaroles, continuous gas emissions, and frequent small eruptions indicate an open and hot pathway for magma ascent to the near-surface. At the summit vent level, lava domes have typically plugged the uppermost part of the conduit except during eruptions when magmatic pressure built and new domes composed of mostly degassed magma extruded and collapsed or much more infrequently, gas-rich explosive eruptions occurred.

The lack of large explosive eruptions at Merapi during the several decades preceding 2010 is attributed to extensive degassing during ascent of the magma through the volcano's subsurface plumbing

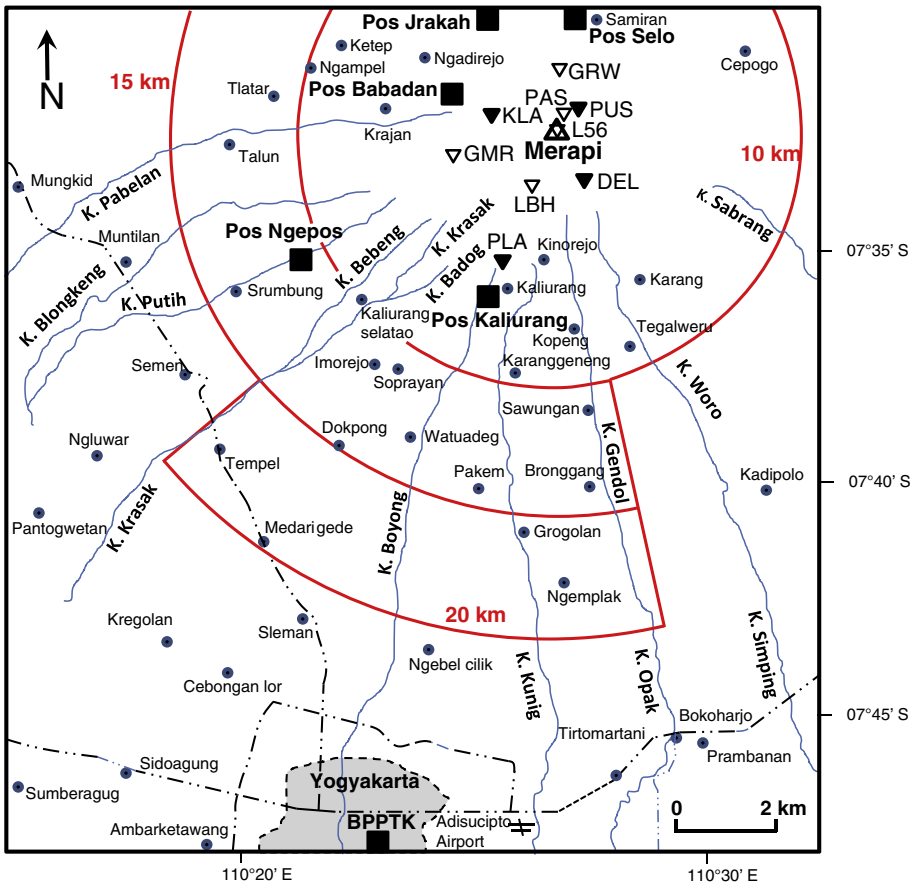

Fig. 1. Index map showing the location of Merapi volcano summit and other features referred to in the text, e.g., observatory post stations ("Pos" in Indonesian), the Merapi Observatory and Technology Center (BPPTK), major drainages (abbreviated "K." for "Kali" in Indonesian), short-period permanent seismic stations (full inverted triangles, PUS, DEL, PLA, KLA), temporary broadband stations (empty inverted triangles, LBH, GMR, GRW, PAS, L56 = WOR at summit). Cities and towns are indicated by name. In addition, hundreds of smaller villages are present on the flanks of the volcano. Major highways are indicated by heavy dashed–dotted lines and the red arcs at 10, 15, and 20 km radius distances from the summit indicate evacuation zones that were put into effect at different times during the eruptive activity (see text for details).