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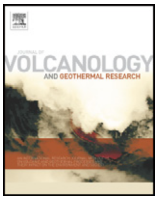

Editorial

The 2010 eruption of Merapi volcano

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1. Introduction

The October–November 2010 eruption of Merapi volcano, near Yogyakarta in Central Java (Fig. 1A), Indonesia was a landmark event. It was the largest eruption in more than 100 years at a volcano that is better known for smaller eruptions, which occur on average every 4–6 years. Typical eruptions of the 20th century produced summit lava domes, which collapsed to produce block-and-ash pyroclastic flows, known as “Merapi-type” pyroclastic density currents. In contrast, the 2010 eruption did not only extrude lava domes (at remarkably rapid rates of up to 35 $m^3\ s^{-1}$), but it also produced several powerful explosions heard up to the southern city of Yogyakarta, vertical eruption columns to 17 km altitude and numerous pyroclastic density currents that extended into populated areas at distances of up to 16 km from the summit.

Because of its frequent activity and dangerous character, Merapi has long been an international “laboratory volcano”. Observatory functions began in the late 1800's and the first seismograph was installed at Merapi in 1924. Currently, the Indonesian Center for Volcanology and Geologic Hazard Mitigation (CVGHM, formerly known as the Volcanological Survey of Indonesia, VSI) operates a technology development center (Balai Penyelitikan dan Pemgembagan Teknologi Kegunungapian) and Merapi Volcano Observatory (MVO) in Yogyakarta to monitor and study Merapi volcanic activity. MVO operates five observatory outposts (“Pos”) at strategic locations on the flanks of Merapi volcano (Fig. 2). The mission of these entities is to forecast eruptions, to improve knowledge of volcanic processes, and to develop new volcano monitoring technology.

Continuous research efforts have been underway at Merapi for decades, with numerous Indonesian and international projects directed at understanding the structure and the mechanisms of dome-collapse “Merapi-type” eruptions and at improving eruption forecasting. Numerous Indonesian scientists have conducted advanced degree programs on Merapi, both at Indonesian universities and abroad. In exchange, several dozen foreign students chose Merapi as the subject for their advanced degrees and many more Indonesian, foreign students, and government scientists have conducted collaborative research and hazard mitigation projects together at Merapi. In line with the international research effort, the “Merapi Decade 1990–2000” ended with a Special Issue of JVGR in 2000, which was organized by Barry Voight, Radan Sukhyar and A.D Wirakusumah (Voight et al., 2000a). An important lesson from this special issue was the warning posed by several authors, that Merapi volcano is capable of much larger eruptions than those of the 20th century, eruptions that could have disastrous consequences (Andreastuti et al., 2000; Camus et al., 2000; Newhall et al., 2000; Voight et al., 2000b). International cooperation in addressing volcano hazards at Merapi (and elsewhere in Indonesia) has built international trust and friendship; these were important factors in managing the response to the 2010 eruption. International cooperation has continued through post-eruption research, as is evident in the authorship of the papers in this special issue.

2. 2010 eruption summary

Eruptions at Merapi are so common and their precursors and effects are so predictable that when Merapi began to experience seismic swarms in late 2009, which then increased in frequency and were accompanied by inflation in 2010, the MVO anticipated another eruption much like the previous ones. For example, during the last eruption (in 2006) a lava dome grew at rates 2 to 4 m^3s^{-1} and added ~$5 \times 10^6\ m^3$ of basaltic–andesite to the complex of pre-existing lava domes at the summit (Ratdomopurbo et al., 2013). Over a period of about 2 months the 2006 dome collapsed repeatedly; the largest pyroclastic density current descended 7 km down the south flank and killed two persons, who took refuge in a tunnel that had been built for their protection.

In early October 2010, when the rate of cumulative seismic energy release approached levels comparable with those of past eruptions, MVO forecasted an eruption for mid-October (Fig. 3). However, during the third week of October, the cumulative seismic energy and extent of deformation exceeded forecast values and CO_2 emissions spiked. As seismicity and summit deformation continued to increase at rates much greater than those preceding previous eruptions, CVGHM concluded that a much larger eruption was coming (Fig. 2 and Surono et al., 2012). The 2010 eruption started with a powerful phreatomagmatic blast on 26 October, which killed 34 people including the renowned spiritual guardian of the volcano (Mbah Marijan). The eruption continued and reached a climactic phase during the night of 4–5 November, with a vertical ash column and with pyroclastic density currents that swept a broad region on the southern flank of the volcano towards Yogyakarta. Satellite remote sensing aided forecasting during the eruptive crisis. These data revealed a new lava dome at the summit, which grew at exceptionally rapid rates (>25 m^3s^{-1} on average) and reached $5 \times 10^6\ m^3$ volume just before the climactic eruption (Surono et al., 2012; Pallister et al., 2013). In addition to volcano-tectonic (VT) and multi-phase (MP) swarms (Budi-Santoso et al., 2013), very

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long-period (VLP) and long-period (LP) earthquakes preceded the eruption and were linked to magma ascent and to regional tectonic activity (Surono et al., 2012; Jousset et al., 2013). The 4–5 November eruption was a “100-year event” (Surono et al., 2012). It was approximately 10 times larger and more explosive than eruptions of the past several decades, and it validated the concern that had long been apparent at Merapi — that much larger and more hazardous eruptions, like the one that took place in 1872, are a continuing threat at the volcano (Andreastuti et al., 2000; Camus et al., 2000; Newhall et al., 2000; Voight et al., 2000b). Recognizing the magnitude of the eruption and the potential threat of additional eruptions, following the 5 November eruption the President of Indonesia requested assistance from the international community.

3. Response to the 2010 eruption

The Geological Agency of Indonesia (parent agency for CVGHM, BPPTK and MVO) monitored the eruptive activity and issued warnings and recommendations for areas to be evacuated. The Indonesian national emergency response agency (BNPB) and their provincial and local counterparts managed the evacuations. Teams from Europe (MIAVITA Project), the U.S.A. and Japan assisted during the crisis and provided new monitoring equipment, remote sensing information and consultation regarding potential hazards. Space agencies from several nations provided remote sensing data (e.g., Canada, Europe, Italy, Japan and U.S.A.), including support through the International Charter for Space and Natural Disasters, which was activated and managed by the U.S. Geological Survey on behalf of the Government of Indonesia.

During the 2 weeks preceding the climactic eruption (which took place just after midnight on 5 November 2010 local time) alert levels and evacuation zones were progressively increased. Tragically, ~380 lives were lost, but because of the effective warnings by CVGHM and the response by BNPB and their provincial and local counterparts, 10,000 to 20,000 lives were saved by evacuations (Surono et al., 2012; Mei et al., 2013).

Over the succeeding 2 years, members of CVGHM, Indonesian universities, and international scientists have studied the monitoring data and deposits from the 2010 eruption in order to better understand what triggers such “larger-than-normal” eruptions. In response to the 2010 eruption, new hazard mitigation and scientific investigations are now underway at Merapi. These include an international science partnership funded by the French National Research Agency (ANR), “DOMERAPI,” which involves numerous Indonesian and international scientists. Also, through funding from the Japanese International Cooperation Agency (JICA) a new continuous GPS monitoring system has been installed. In addition, a new lahar monitoring system was installed by MVO using instruments provided by the U.S. Agency for International Development and U.S. Geological Survey (Volcano Disaster Assistance Program, VDAP).

In recognition of the international collaboration at Merapi and the effective and life-saving cooperation between volcano science and emergency management in Indonesia, CVGHM will host the 8th Cities on Volcanoes (COV) meeting in Yogyakarta during 2014. This meeting is organized under the Cities and Volcanoes Commission of the International Association of Volcanology and Chemistry of the Earth's Interior, with the purpose of bringing together volcanologists, city authorities, sociologists, psychologists, emergency managers, economists and city planners to evaluate volcanic crises preparedness and management in cities and densely populated areas.

4. Highlights of this special issue

In April 2011, a special session of the European Geophysical Union (EGU) was convened to bring the scientists working on Merapi together to share data on the eruption response and initial results of investigations on the geophysics and geology of the eruption. More than 30 presentations were given at this EGU meeting (Jousset et al., 2011) and an agreement was reached among participants to produce this special issue of the Journal of Volcanology and Geothermal Research.

The issue includes 23 original papers covering a wide range of topics, including contributions on pre-eruptive conditions, tectonic setting and structure of Merapi, a review of the 2006 and past eruptions, and papers on interpretation of satellite remote sensing, seismology, geodesy, physical volcanology, petrology, observations and modeling and impacts and risks, as well as lessons learned from the massive evacuation of ~400,000 people. We summarize below these results.

The issue begins with a review of results from the MERapi AMPhibious EXPeriment, which reveal a large (>50,000 km^3) low-velocity body that extends to upper mantle depths beneath Central Java. This anomaly may constitute the pathway for magmas erupted at Merapi and at the other active volcanoes in the region (Luehr et al., 2013). A series of contributions document pre-eruption conditions in the shallow magmatic system and provide details of the last eruption before 2010 — the 2006 eruption, a prolonged event that produced a summit dome and multiple Merapi type pyroclastic density currents. The 2006 eruption eroded the pathway for flows into the Gendol valley, the principal site for flows in 2010 (Innocenti et al., 2013a,b; Preece et al., 2013; Ratdomopurbo et al., 2013; Walter et al., 2013).

Budi-Santoso et al. (2013) demonstrate the exceedingly high rates of change in monitoring parameters (seismicity, deformation, gas emissions), which preceded and were used to forecast the 2010 eruption. For the first time, satellite radar data played an equal role to *in situ* monitoring in issuing eruption warnings during a major crisis (Pallister et al., 2013). The use of satellite radar and other remote sensing data also played a role in forecasting and evaluating the extent of impacts and volumes of deposits (Bignami et al., 2013; Pallister et al., 2013). Although localized deformation of the summit area was much larger than that preceding previous eruptions (as revealed by repeat surveying with EDM; Surono et al., 2012), Saepuloh et al. (2013) use D-InSAR data to show that broader (regional) deformation was not observed. However, these data may indicate three episodes of inflation during the 2006–2010 intra-eruptive period and they relate these episodes to upward transfer of magma from deep to shallow reservoirs. Advanced seismic analyses for the 2010 eruptive cycle document the ascent and change in frequencies of volcanic earthquakes as magma and fluids ascended, resonated in fractures, and erupted (Budi-Santoso et al., 2013; Jousset et al., 2013). In addition, peaks in eruptive activity may have been triggered by regional earthquakes (Jousset et al., 2013).

Field investigations document the volumes and characteristics of deposits from the eruption, including evidence of a lateral blast and focusing of energy from flowage through constrictions in channels, which resulted in extensive and deadly overbank surges (Charbonnier et al., 2013; Cronin et al., 2013; Jenkins et al., 2013; Komorowski et al., 2013). Petrologic studies explain the explosive character of the eruption as the result of rapid rise of an anomalously large batch of magma and gas from a deep reservoir below the volcano (Costa et al., 2013), likely including additional CO$_2$ derived from assimilation of crustal limestone (Borisova et al., 2013; Troll et al., 2013). The investigation of magmatic

Fig. 1. (A) Eruption column from Merapi volcano, on 6 November 2010, following the climactic eruption during the night of 4–5 November. Photograph by Clara Prima, AFP. (B) Summit of Merapi volcano, before and after the 2010 eruption. Photographs by BPPTK (Surono et al., 2012) (C) The new crater of Merapi on 8 September 2011, seen from the west rim. We can distinguish in the center of the lava dome tephra that erupted on 6–20 November. Photograph Courtesy by F. Beauducel (IPGP).