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Analysis of the seismic activity associated with the 2010 eruption of Merapi Volcano, Java

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ABSTRACT

The 2010 eruption of Merapi is the first large explosive eruption of the volcano that has been instrumentally observed. The main characteristics of the seismic activity during the pre-eruptive period and the crisis are presented and interpreted in this paper. The first seismic precursors were a series of four shallow swarms during the period between 12 and 4 months before the eruption. These swarms are interpreted as the result of perturbations of the hydrothermal system by increasing heat flow. Shorter-term and more continuous precursory seismic activity started about 6 weeks before the initial explosion on 26 October 2010. During this period, the rate of seismicity increased almost constantly yielding a cumulative seismic energy release for volcano-tectonic (VT) and multiphase events (MP) of 7.5×10^{10} J. This value is 3 times the maximum energy release preceding previous effusive eruptions of Merapi. The high level reached and the accelerated behavior of both the deformation of the summit and the seismic activity are distinct features of the 2010 eruption.
The hypocenters of VT events in 2010 occur in two clusters at of 2.5 to 5 km and less than 1.5 km depths below the summit. An aseismic zone was detected at 1.5–2.5 km depth, consistent with studies of previous eruptions, and indicating that this is a robust feature of Merapi's subsurface structure. Our analysis suggests that the aseismic zone is a poorly consolidated layer of altered material within the volcano. Deep VT events occurred mainly before 17 October 2010; subsequent to that time shallow activity strongly increased. The deep seismic activity is interpreted as associated with the enlargement of a narrow conduit by an unusually large volume of rapidly ascending magma. The shallow seismicity is interpreted as recording the final magma ascent and the rupture of a summit-dome plug, which triggered the eruption on 26 October 2010.
Hindsight forecasting of the occurrence time of the eruption is performed by applying the Material Failure Forecast Method (FFM) using cumulative Real-time Seismic Amplitude (RSAM) calculated both from raw records and on signals classified according to their dominant frequency. Stable estimates of eruption time with errors as small as ± 4 h are obtained within a 6 day lapse time before the eruption. This approach could therefore be useful to support decision making in the case of future large explosive episodes at Merapi.

1. Introduction

Merapi is located on Java Island, about 30 km north of the city of Yogyakarta. It is considered as one of the most dangerous volcanoes of Indonesia because of densely populated surroundings and high levels of eruptive activity. The recent history of Merapi (Voight et al., 2000) is characterized by two eruptive styles: 1) effusive growth of viscous lava domes, with typical recurrence of 4 to 6 years, which collapse gravitationally to produce pyroclastic flows known as «Merapi-type nuées ardentes», 2) exceptional explosive eruptions of relatively large size, associated with column collapse and pyroclastic flows that reach or exceed distances of 10–15 km from the summit. The October–November 2010 eruption is the first large explosive event (VEI ~4) at Merapi that has been recorded by a multi-parametric monitoring network. It is also the first modern eruption that was not preceded by emergence of a lava dome. For example, previous instrumentally observed VEI = 1–2 eruptions in 1984, 1986, 1992, 1994, 1997, 1998, 2001, and 2006 were all characterized by lava extrusion followed by dome collapses. Consequently there is a unique opportunity to compare

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the seismic activity associated with the two types of eruption and to look for precursory evidence of a transition between effusive and explosive styles.

As for most volcanoes in the world, the seismic activity of Merapi is characterized by a large variety of events that correspond to different locations and physical processes of the sources. Since 1984, the classification of events at Merapi includes the following types: deep (VTA) and shallow (VTB) volcano-tectonic, multiphase (MP), low frequency (LF), very long period (VLP) events, tremor and rock fall (Ratdomopurbo and Poupinet, 2000). Hypocenter distributions of VT events from past eruptions display an aseismic zone at 1.5–2.5 km depth, which has been interpreted as a ductile high-temperature zone (Ratdomopurbo and Poupinet, 2000; Wassermann and Ohrnberger, 2001; Hidayati et al., 2008).

Eruptions at Merapi are generally preceded by VT and MP seismicity on varying time scales from weeks to months (Ratdomopurbo and Poupinet, 2000; Voight et al., 2000; Suharna et al., 2007). However, at least two of the past eruptions were not preceded by significant increases in seismicity (1986 and 1994) and these are interpreted as gravitational collapses of summit domes. During the 1991 eruption, about 25% of the shallow VT events were seismic multiplets. These were families of events with similar waveforms and are interpreted to indicate either sources very close to each other and with identical focal mechanisms or to non-destructive and repetitive sources. Ratdomopurbo and Poupinet (1995) analyzed multiplets during 1992 using a cross-spectral method comparison of coda waves. They detected an increase of 1.2% in seismic velocity, possibly related to the pressurization of the magma feeding system. Using records of a repeatable controlled source, Wegler et al. (2006) also observed an increase of the shear wave velocity before the 1998 eruption.

The velocity structure of Merapi is still poorly known. Active experiments using air gun shots have been carried out to investigate this structure (Lühr et al., 1998; Wegler et al., 1999). But, because the direct P- and S-waves generated by surficial sources were rapidly attenuated by scattering within the heterogeneous volcanic medium, no velocity model could be obtained. However, spindle-like shapes of seismogram envelopes were explained by a diffusion model (Wegler and Lühr, 2001). Lacking a more detailed velocity model, hypocenter determinations at Merapi generally use a homogeneous model with P-wave velocity of 3 km s^{-1} (Ratdomopurbo, 1995; Hidayati et al., 2008) or 2.8 km s^{-1} (Wassermann and Ohrnberger, 2001). At a broader scale, tomographic analysis (Koulakov et al., 2007, 2009; Wagner et al., 2007) reveals an exceptionally strong low velocity anomaly in the crust between the Merapi and Lawu (east of Merapi) volcanic groups. This anomaly is interpreted as a fluid and melt bearing magmatic feeder zone for the volcanoes in the area.

Focal mechanisms of VT events recorded in 2000–2001 were estimated by Hidayati et al. (2008) using both polarity and amplitude of P-wave first motions. VTA and most deep VTB events are of normal-fault types; whereas, VTB events located close to the surface yield both reverse and normal fault solutions.

Hidayat et al. (2000, 2002) studied very-long period (VLP) events that occurred in 1998 and determined that these have periods of 6–7 s, display similar waveforms from event to event, and are coeval with MP or LF earthquakes. They carried out moment tensor inversion of the waveforms and proposed a source model consistent with a dipping crack located at about 100 m depth under the 1998 dome. They suggested a source process involving the sudden release of pressurized gas through the crack over a time span of about 6 s. No VLP events were observed during the active periods of 2001 and 2006; whereas, a significant number of VLP events were observed in 2010 prior to and during the eruption (Jousset et al., 2013).

In this paper, we focus on seismic activity that accompanied the 2010 eruption, as well as activity during the year preceding the eruption. We describe the types of seismic events observed and provide a detailed chronology of the seismicity during this period. In particular, the spatial and temporal distribution of the VT earthquake hypocenters yields important information bearing on pre-eruptive processes. We apply the Material Failure Forecast Method (Voight, 1988) to the RSAM values and test the potential of this approach to forecast the time of the eruption onset. Comparisons of seismicity between 2010 and earlier eruptions give some insights into precursory seismic features that may be used to distinguish explosive from effusive eruptions.

2. Seismic network

The monitoring system of Merapi is operated by BPPTK (Balai Penyelidikan dan Pengembangan Teknologi Kegunungapian), which belongs to CVGHM (Center of Volcanology and Geological Hazard Mitigation). Monitoring of Merapi is mainly based on seismic, deformation and geochemical measurements. A permanent seismic network consists of four short-period (SP) stations equipped with L4C and L22 seismometers. Signals are transmitted to Yogyakarta by radio with VHF modulation and are digitized by a Güralp DM16S acquisition system at a rate of 100 samples per second with 16 bits accuracy. SP stations have been used as reference stations in routine analysis, such as event classification and counting, source location and seismic energy calculations. In addition, up to six broadband (BB) stations using Güralp CMG-40TD seismometers with period 60 s and TCP/IP protocol for data transmission were operated between July 2009 and February 2010. Both types of stations use GPS clocks for synchronization and Güralp Compressed Format (GCF) for data file storage. Fig. 1 shows the configuration of the monitoring network; seismic stations are located on and around the volcano at distances to the crater ranging from 0 to 6 km.

Some breakdowns in stations reduced the amount of available records during the 2010 pre-eruptive period (Fig. 2). Furthermore, the GPS clocks of some broadband stations failed during several time intervals. In order to use arrival times from these stations for source location, a procedure of clock re-synchronization, based on seismic noise correlation (Stehly et al., 2007; Sens-Schönfelder, 2008) was applied. The cross-correlation function (CCF) of the noise recorded in two stations is directly related to the Green function between the two sites (e.g. Campillo, 2006). When the clock of one of the stations has drifted, the CCF is delayed by the same lag with respect to that obtained when both clocks are synchronized. Thus, by looking for the maximum of the correlation function between the shifted and the reference CCF, it is possible to estimate the delay and to synchronize the stations. An estimated precision of ~0.05 s is obtained with this approach, which uses low-pass (<4 Hz) filtered signals (Fig. 3).

3. Main features of the seismic events

For consistency, the same classification of seismic signals has been used at Merapi since the initial installation of a telemetered network in 1982 (Ratdomopurbo, 1995; Ratdomopurbo and Poupinet, 2000). The main types of signal are classified as volcanotectonic (VT), multiphase (MP), low-frequency (LF), rockfall (RF), and tremor. VT events are characterized by clear onsets and high frequency content (up to 25 Hz). These types of events are similar to common tectonic earthquakes and are attributed to brittle failure of rock; they have mostly simple double-couple mechanisms (McNutt, 1996). The main difference relative to tectonic earthquakes is that VT events are related to volcanic activity, they frequently occur in swarms, and thus they do not follow a main shock–aftershock progression (McNutt, 2000).

VTs at Merapi are sub-divided into deep (VTA) and shallow (VTB) events (Fig. 4). VTA events are characterized by hypocenters at depths greater than 2 km below the summit, and they have clear P- and S-wave arrivals. VTB events have depths less than 2 km and they have more emergent onsets at distant stations. For some VTB events, S-waves cannot be distinguished. VTA and VTB events are