Volcanic activity influenced by tectonic earthquakes: Static and dynamic stress triggering at Mt. Merapi

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[1] Mt. Merapi is one of the most dangerous volcanoes in Indonesia, located within the tectonically active region of south-central Java. This study investigates how Mt. Merapi affected - and was affected by - nearby tectonic earthquakes. In 2001, a Mw6.3 earthquake occurred in conjunction with an increase in fumarole temperature at Mt. Merapi. In 2006, another Mw6.3 earthquake took place, concomitant with an increase of magma extrusion and pyroclastic flows. Here, we develop theoretical models to study the amount of stress transfer between the earthquakes and the volcano, showing that dynamic, rather than static, stress changes are likely responsible for the temporal and spatial proximity of these events. Our examination of the 2001 and 2006 events implies that volcanic activity at Mt. Merapi is influenced by stress changes related to remote tectonic earthquakes, a finding that is important for volcano hazard assessment in this densely inhabited area. **Citation:** Walter, T. R., R. Wang, M. Zimmer, H. Grosser, B. Lühr, and A. Ratdomopurbo (2007), Volcanic activity influenced by tectonic earthquakes: Static and dynamic stress triggering at Mt. Merapi, *Geophys. Res. Lett.*, *34*, L05304, doi:10.1029/2006GL028710.

1. Introduction

[2] In earthquake research, most sensitive aftershock studies suggest that the threshold of static stress triggering is at about 10 kPa [*Stein*, 1999]. In some cases even an effect of the earth tides (1 kPa) is proposed [*Tanaka et al.*, 2004]. Such stress changes may also alter fluid flow within the shallow crust, as shown by the numerous studies of tectonic earthquakes that occurred simultaneously with changes in the eruption dynamics of volcanoes, geysers and hydrothermal reservoirs [*Linde and Sacks*, 1998; *Hill et al.*, 2002; *Gudmundsson and Brenner*, 2003; *Marzocchi et al.*, 2004; *Wang et al.*, 2004; *Manga and Brodsky*, 2006; *Walter and Amelung*, 2006]. The triggering effect may even act at large distances, as very small changes of the stress field may activate a system that is in a near critical state [*Hill et al.*, 2002]. However, the mechanism by which volcanoes are triggered and whether they are influenced mainly by transient stress changes (e.g., caused by the passing of seismic waves) or by permanent stress changes (static displacement) remains unknown. Understanding how stress triggering works is important for the interpretation of precursors, early warning and hazard assessment - especially for volcanoes that are known for their unpredictable and violent explosive behavior. Here, the stress transfer between Mt. Merapi and nearby tectonic earthquakes is studied.

[3] Although Mt. Merapi is one of the most active and dangerous volcanoes in the world, the area surrounding Mt. Merapi is nonetheless densely populated with the land being used up to the mid-flanks. Mt. Merapi is located in a region where critical stresses build up during convergence of the Indo-Australian and Eurasian plates. The stratovolcano is of basaltic–andesitic composition, with a dome complex that grows in an older crater [*Voight et al.*, 2000]. Typical eruptions start with dome extrusion accompanied by its partial collapse, causing rock falls and pyroclastic avalanches. Earlier work has suggested that Merapi can be influenced by extrinsic processes such as earthquakes [*Richter et al.*, 2004], or climatic changes [*Friedel et al.*, 2004]. The effect of earth tides [*Jousset et al.*, 2000] could not be confirmed [*Neuberg*, 2000], thus the threshold above which stress triggering may occur at Mt. Merapi is likely to be higher than typical earth tide values. The influence of an increase in volcanic activity after earthquakes has been discussed for several eruptions (in 1823, 1835, 1840, 1902, and 1943), some of which might indeed have been related to regional-tectonic earthquakes [*Voight et al.*, 2000]. Since modern instrumentation, however, the 2001 and 2006 Mt. Merapi events are the only clear accounts that show a response occurring concomitantly with an earthquake. As described below, both the 2001 and 2006 earthquakes may have influenced the Mt. Merapi volcano by stress transfer.

2. Earthquake - Volcano Activity in 2001 and 2006

[4] The two most recent eruptions at Mt. Merapi culminated in 1/2001 and in 6/2006 in conjunction with two earthquakes, raising the question whether Mt. Merapi is interacting with tectonic earthquakes in a two-way mode. In the following discussion, we will first investigate if magma accumulation under Mt. Merapi may have triggered the earthquakes. Second, we will examine if stress changes related to the earthquakes may explain the increase in volcanic activity at Mt. Merapi.

[5] Both the 2001 and 2006 earthquakes had a magnitude of Mw6.3. The 2001 earthquake occurred at S8.070 E110.240, at a horizontal distance of ~50 km SW of Mt. Merapi (Figure 1). The depth of the earthquake was at ~130 km, thus matching the depth of the subducting slab under this region. Harvard focal mechanism suggests a fault plane with a strike of 49°, a dip of 32° and a slip of −158° (or 300°, 79°, −60°, respectively). At this time Mt. Merapi was already in a phase of higher volcanic activity, being closely monitored within the Indonesian - German collaboration project MERAPI [*Zschau et al.*, 1998]. Gas composition

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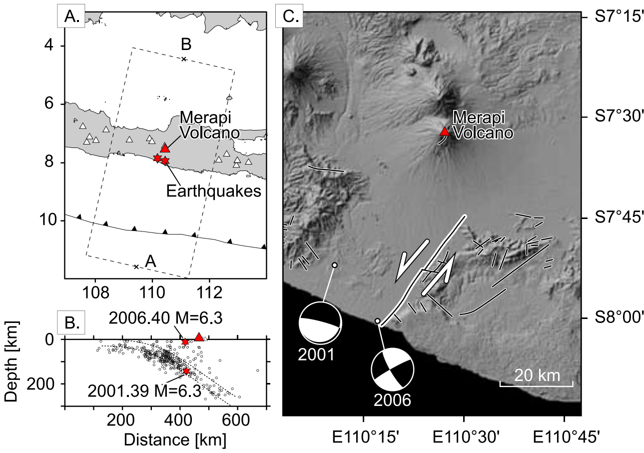

Figure 1. Study area. (a) Geographic location of Mt. Merapi, Mw6.3 earthquakes of 2001 and 2006. (b) Cross-section through A-B shows earthquake hypocentres. Red symbols are earthquakes (stars) and Mt. Merapi (triangle). (c) Shaded relief map of the district of Yogyakarta, with Mt. Merapi and the M6.3 earthquake epicenters. Known fault traces are oriented NE-SW (shown in bold) and a less developed trend striking WNW-ESE (thin black lines). Seismic data and focal mechanisms after NEIC catalogue.

and temperature was measured using a specially designed set of analytical instruments, including a temperature sensor that operated successfully over several months in the high temperature fumaroles at the summit of Mt. Merapi [*Zimmer and Erzinger*, 2003]. Measurements in 2001 were performed at about 200 m SE of the center of the summit crater (Station ''Woro''). Temperatures before the 25/5/2001 earthquake were approximately 435°C. Coinciding with the tectonic earthquake, we measured a sudden increase of about 30°C in the fumarole temperature (Figure 2a). The temperature remained at this high level for several days until the equipment was destroyed by an eruption.

[6] After ~4.5 years of relative quiescence, Mt. Merapi started a new eruptive phase. A gradual increase of the seismicity was detected in 3/2006, so that about 10,000 inhabitants were warned to prepare for evacuation. By 11/5/2006, the first pyroclastic avalanche was reported, and by mid May the Alert Level was raised from 3 to 4 (the highest level) and 22,000 people were evacuated. These actions were overtaken by an earthquake with a magnitude of Mw6.3 occurring on 27/5/2006 5:53 local time (26/5/2006 22:54 UTC), 16 days after the first pyroclastic avalanche. The location of the earthquake epicenter was at S8.00 E110.49, again 50 km south of Mt. Merapi. This time, however, the event was shallow at <30 km depth. The fast moment tensor solution suggested a strike-slip event with fault strike 51°, dip 90° and slip of 14° (or 321°, 76°, 180°). Geologic studies have already noted the presence of a major shallow fault with surface traces oriented N035E (Figure 1c), at exactly the location of the 2006 epicenter that had a focal mechanism nodal plane similar than the fault trace. The earthquake caused ~6,000 fatalities and substantial damage to the infrastructure within an area as large as ~500 km^2. At Mt. Merapi, analysis of seismic signals by the scientific staff of the volcano observatory in Yogyakarta [*Ratdomopurbo and Poupinet*, 1995] that allows the number of pyroclastic avalanches (PA) to be counted [*Ratdomopurbo and Poupinet*, 2000], shows a remarkable PA increase after the earthquake. During the 16 days prior to the earthquake, a total of 537 PA occurred, which represents a mean of about 34 PA/day (Figure 2b). The daily volume of dome growth was about 50,000 m^3. During the 16 days after the earthquake, however, the dome collapse activity increased to 1523 PA, giving an average of over 95 PA/day. The daily volume of dome growth was estimated to be >150,000 m^3. This data suggests the earthquake was followed by a three-fold increase of dome growth and dome collapse activity at Mt. Merapi (Figure 2b).

3. Stress Field Modelling

[7] Theoretical models were designed to take into account the following scenarios: (1) the pre-eruptive inflation of Mt. Merapi and the associated stress change at the shallow fault, and inversely, (2) the tectonic fault dislocation due to the Mw6.3 earthquakes and associated stress change at Mt. Merapi. Here we simulate dislocations in linear elastic half-space models using methods based on the works by others [*Mogi*, 1958; *Okada*, 1992].

[8] The pre-eruptive inflation was simulated by an expanding spherical-symmetrical point source using analytical dislocation software [*Toda et al.*, 1998]. The models are a first order approximation as the location and volume change of an inflating magma chamber under Mt. Merapi are not well known. A small chamber was proposed at about 1.5 km depth, and possibly a larger one below 6 km depth [*Ratdomopurbo and Poupinet*, 1995]. The volume of expansion is somewhat constrained by the volume of the eruption, which can be considered as a maximum value of inflation. Here we assume that the entire volume of the 2006 erupted magma, 8 Mm^3, was accumulating at 6 km depth before the earthquake. In terms of stress transfer, this is the ''worst case scenario'' which nevertheless may help in understanding whether Mt. Merapi is capable of triggering

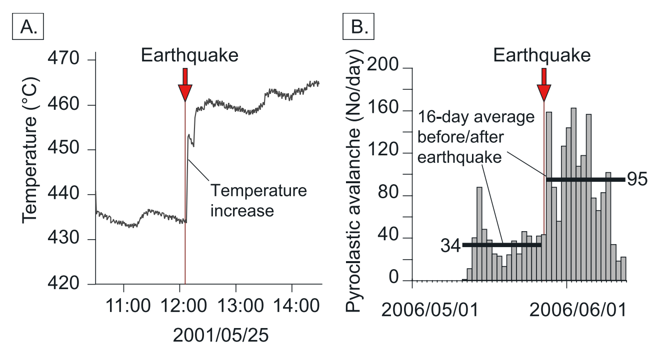

Figure 2. Changes at Mt. Merapi that correlate with the 2001 and 2006 earthquakes. (a) Temperature increase in 2001 at the high-T fumarole field ''Woro,'' about 200 m SE of the summit of Mt. Merapi at 5:06 local time. (b) Increase of the number of pyroclastic avalanches. The 16 days before the 2006 earthquake, 34 daily pyroclastic avalanches occurred on average. After the earthquake, this daily number is at 95. Not shown is that the eruption further continued and peaked on 14 June with a 7 km long PA.

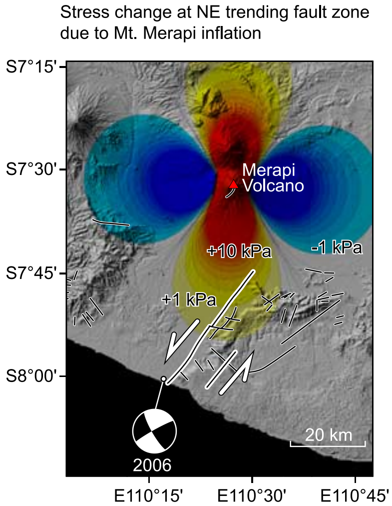

Figure 3. Inflation model considering a volume increase of 8 Mm^3 under Mt. Merapi at 6 km depth ("worst case scenario," see text for details). Shown are the resulting changes of the Coulomb failure stress at vertical left lateral strike slip faults that strike N035E at a depth of 10 km. Red colors mean that fault slip is encouraged, blue means that fault slip is discouraged. The magnitude of stress changes at the NE-SW trending faults are below 1 kPa, and thus it is unlikely that inflation had a major triggering effect for the earthquake.

such a tectonic earthquake. We calculated the Coulomb failure stress CFS on faults parallel to the N035E trending left-lateral strike-slip fault where the 2006 earthquake occurred [*Toda et al.*, 1998]. The results show that CFS increased at the fault zone (Figure 3). However, the magnitude of stress changes are small (0.1 – 1 kPa), i.e., even smaller than tidal changes (1 kPa). In comparison, because the 2001 earthquake was located at a much greater depth (130 km) and therefore at much greater distance (140 km) to the magma source, even less stress changes are expected (<0.1 kPa, these results are not shown in Figure 3). To summarize, Mt. Merapi could have had only a minor contributing effect for the occurrence of the May 2006 earthquake.

[9] In addition we test how the 2001 and 2006 earthquakes caused a stress change at the volcano by calculating synthetic seismograms at the Merapi site. Except for the different focal mechanisms and hypocenter depths as given by the NEIC Catalogue, we used the same model for the rupture process of the two earthquakes. Both model events have a seismic moment of 3×10^{18} Nm and rupture a rectangular area of 15 km (along strike) $\times$ 10 km (along dip). This ruptured area is meshed by a grid size of 1 km $\times$ 1 km, resulting in 150 discrete point sources. These point sources are triggered by the rupture front propagating circularly from the hypocenter at a constant velocity of 2 km/s. The seismic moment of each point source is released via a set of Brune's sub-events [*Brune*, 1970], the points distribution being subject to the Gutenberg-Richter law in size and being random in time. Use of this randomness ensures that adjacent point sources are reasonably coherent at low frequency, but incoherent at high frequency [e.g., *Irikura*, 1983]. The characteristic duration of each point source is comparable with the rise-time of the earthquake which is related empirically with the magnitude and the stress drop [*Boore*, 1983]. Using the semi-analytical code by *Wang* [1999], we calculated the Green's functions for the standard seismic reference model IASPEI91. The cut-off frequency of the Green's functions is about 8 Hz. Synthetic seismograms of the two earthquakes are obtained by convolution between the Green's functions and the source functions described above. For calibration of our synthetic seismograms, we used the velocity seismograms as recorded by the GEOFON station UGM (see http://www.gfz-potsdam.de/geofon). By optimizing the rupture velocity and the stress drop of the earthquakes iteratively, we were able to reproduce the same signal duration and amplitude as observed for the two earthquakes. We then calculated synthetic pressure seismograms at the location of Mt. Merapi. The results are presented for two different depths under Mt. Merapi, at the surface, and at 5 km depth (Figure 4).

[10] The synthetic seismograms show the different arrival times of the seismic waves, being approximately 20 s for the 2001 earthquake (140 km distance) and 10 s for the 2006 earthquake (50 km distance). Moreover, our models predict two main "types" of pressure changes under Mt. Merapi, i.e., a transient pressure change within the first 20 seconds after arrival of the seismic waves, and a static pressure

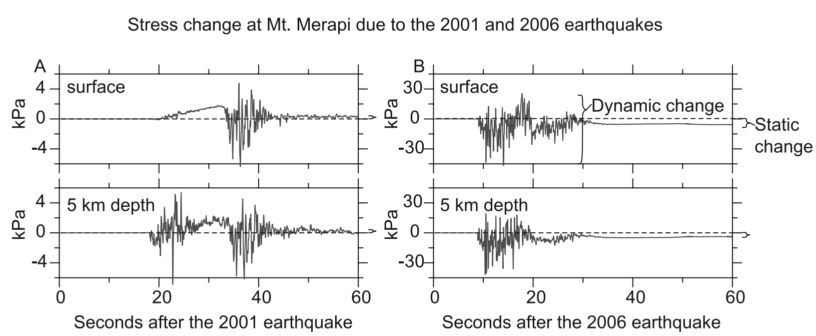

Figure 4. Earthquake models considering the two Mw6.3 earthquakes of 2001 and 2006. Shown are the resulting dynamic changes of the pressure at the surface and at 5 km depth, where the pressure is the volumetric strain multiplied by the bulk modulus. Dynamic pressure fluctuations occur at >1 Hz for about 20 s. The peak-to-peak pressure change is about 10 kPa for the 2001 event and 60 kPa for the 2006 event. This may have increased degassing and dome growth at Mt. Merapi (see discussion).

change (Figure 4). Most notably, the transient pressure change has peak-to-peak values of about 10 kPa for the 2001 and 60 kPa for the 2006 earthquake, lasting about 20 s only. In contrast, the static pressure change is well below 10 kPa, about 0.3 kPa for the 2001 earthquake and about −3 kPa for the 2006 earthquake. Although the 2001 earthquake caused a positive static stress change, and the 2006 event a negative static stress change, both earthquakes led to an increase on the volcanic activity at Mt. Merapi, implying that the static stress can not be the major player. Moreover, under consideration that 10 kPa may serve as a critical threshold for stress triggering [*Stein*, 1999], static triggering from or to the volcano probably had only a minor influence. The dynamic stress changes, in contrast, may have had an important triggering effect as we will discuss below.

4. Discussion

[11] Different types of earthquake-induced activity changes may occur in volcanic areas. In some cases new eruptions begin [*Linde and Sacks*, 1998], local volcano-seismic events or degassing increases [*Hill et al.*, 2002], groundwater pressure or geyser eruptions [*Brodsky et al.*, 1998] and hydrothermal activity enhances [*Manga and Brodsky*, 2006]. Quantitative measurements of such volcanic activity changes as well as the amplitude and frequency of earthquake-induced stress changes are still rare, however.

[12] Our models are simplified, assume homogeneous elastic materials and ignore topographic effects. It was proposed that Mt. Merapi behaves mechanically heterogeneous, affecting internal stress field and ground deformation [*Beauducel et al.*, 2006]. Local variations, such as a weak material or a steep topography, may amplify pressure seismograms and hence the triggering effect. Also the location and shape of the inflation source are not well constrained and may affect the results. For example, a different depth and sill or pipe-like reservoir may lead to different stress distributions. Nevertheless, important implications can be drawn from this work. Our models suggest that inflation of Mt. Merapi could have increased the static stress at the 2006 seismogenic fault to minor extent, if any (assuming Merapi had deflated during eruption, the stress would have been reduced at the fault). The Mw6.3 earthquakes, in turn, caused a slight static pressure change under Mt. Merapi. Of much larger scale, however, are the stress changes related to the passing of the seismic waves. The 2001 earthquake caused a fluctuation of compression and decompression change larger than 1 kPa at >1 Hz. Also the 2006 earthquake caused similar frequencies, with about 20–30 peaks larger than 1 kPa, and even 5–10 peaks larger than 10 kPa.

[13] Although numerous studies suggest that static stress triggering may explain the occurrence of earthquakes [*Stein*, 1999], our study adds evidence that the contribution of the passing waves is at least as important at Mt. Merapi. Therefore, our work supports conclusions drawn from earthquake triggering studies by *Brodsky et al.* [1998], *Manga and Brodsky* [2006], and *Pollitz and Johnston* [2006]. A number of possible explanations are summarized in these works, showing that the gas phase within the magma-hydrothermal system may be significantly affected by the passing seismic waves. Gas bubbles embedded in a medium through which seismic waves pass may undergo volume expansion [*Brodsky et al.*, 1998], increasing the pressure by up to a several kPa. At Mt. Merapi, stress changes and shaking may have triggered bubble growth and ascent, indirect effects of which can be measured by means of fumarole temperature (as in 2001) and increased dome extrusion and dome collapse (as in 2006). Although this study suggests that Mt. Merapi can be triggered by regional tectonic earthquakes, we note that this is apparently not the case for all large earthquakes such as the recent subduction earthquakes (Sumatra 12/2004, 5/2005, Java 7/2006).

5. Conclusion

[14] Tectonic earthquakes south of Merapi volcano correlated with an increase of the fumarole temperature in 2001, and an increase of the pyroclastic flows in 2006. Our models show the modes of stress transfer between these earthquakes and Mt. Merapi volcano. For the assessment of the eruption dynamics, our study implies that consideration of a potential extrinsic triggering source is important. Specifically, this means that for the study of volcano and earthquake hazards and early warning of the 3.5 Mio inhabitants in the district of Yogyakarta around Merapi, the coupling of volcanism and tectonic earthquakes needs to be taken into account.

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