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The 26 May 2006 magnitude 6.4 Yogyakarta earthquake south of Mt. Merapi volcano: Did lahar deposits amplify ground shaking and thus lead to the disaster?

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[1] Indonesia is repeatedly unsettled by severe volcano- and earthquake-related disasters, which are geologically coupled to the 5–7 cm/a tectonic convergence of the Australian plate beneath the Sunda Plate. On Saturday, 26 May 2006, the southern coast of central Java was struck by an earthquake at 2254 UTC in the Sultanate Yogyakarta. Although the magnitude reached only $M_w = 6.4$, it left more than 6,000 fatalities and up to 1,000,000 homeless. The main disaster area was south of Mt. Merapi Volcano, located within a narrow topographic and structural depression along the Opak River. The earthquake disaster area within the depression is underlain by thick volcaniclastic deposits commonly derived in the form of lahars from Mt. Merapi Volcano, which had a major influence leading to the disaster. In order to more precisely understand this earthquake and its consequences, a 3-month aftershock measurement campaign was performed from May to August 2006. We here present the first location results, which suggest that the Yogyakarta earthquake occurred at 10–20 km distance east of the disaster area, outside of the topographic depression. Using simple model calculations taking material heterogeneity into account we illustrate how soft volcaniclastic deposits may locally amplify ground shaking at distance. As the high degree of observed

damage may have been augmented by the seismic response of the volcaniclastic Mt. Merapi deposits, this work implies that the volcano had an indirect effect on the level of earthquake destruction.

Components: 4683 words, 7 figures, 1 table.

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1. Introduction

[2] Mount Merapi Volcano, located in central Java (Indonesia, Figure 1), initiated a new eruptive phase after 4.5 years of quiescence, as detected by increasing volcanic seismicity in March 2006 [*Siebert and Simkin*, 2002]. The first pyroclastic avalanche was reported on 11 May 2006, prompting officials to evacuate 22,000 people from the volcanic slopes and northern part of Yogyakarta. Instead of the awaited volcano eruption, however, a devastating earthquake occurred to the south of the volcano. The event was near the city Yogyakarta, on Saturday, 26 May 2006, at 2254 UTC (Sunday, 27 May 2006, at 5:54 A.M. local time). While recent studies have suggested that the earthquake triggered increased activity at Mt. Merapi [*Harris and Ripepe*, 2007; *Walter et al.*, 2007a], it appears that the volcano eruption had only minor contribution to the earthquake [*Walter et al.*, 2007a]. This paper investigates an indirect effect of the volcano. As shown herein, the May 2006 earthquake caused damage to inhabited areas underlain by remobilized volcaniclastic deposits (lahar deposits; see Figure 2) [*Walter et al.*, 2007b]. We analyze the May 2006 earthquake damage area and the first data of aftershock measurements, suggesting that the volcaniclastic sediments underneath the earthquake disaster area played a significant role by amplifying the seismic waves. We show that aftershocks were located at 10–20 km distance eastward of the damage area, and we perform a simulation to study how the ground shaking was amplified by the soft sediments.

2. The 26 May 2006 Earthquake

[3] Teleseismic data suggested that the 26 May 2006 earthquake main shock hypocenter was relatively shallow at 20–30 km distance to the city center of Yogyakarta (Table 1). In this area, the presence of a major southwest-northeast trending fault is thought to limit the area of tectonic subsidence of the Yogyakarta graben [*Rahardjo et al.*, 1977]. As a result, the most likely origin of this earthquake was interpreted to be this dip-slip fault. The fault is striking parallel to the Opak River, hereafter referred to as the Opak River Fault (Figure 3). Along a 30 km stretch of the Opak River Fault, the 26 May earthquake caused severe damage to the densely populated area, leaving about 6,000 dead, 50,000 injured and between 0.5 and 1 million homeless [*Consultative Group on Indonesia* (*CGI*), 2006]. The destructive consequences of the earthquake were unprecedented in this region, with hundreds of thousands houses destroyed or damaged, including destruction of the historical Hindu temples of Prambanan (9th century A.D.) and the Sultans tomb (17th century A.D.) at Imogiri. The total loss is estimated at over 3 billion U.S. dollars [*CGI*, 2006]. There are no written records of similar devastating earthquakes in this region.

[4] The Harvard Centroid-Moment-Tensor (CMT) solution suggests a moment magnitude of M_w = 6.4 (see Table 1), and significant strike-slip rupture to the east of the disaster area (Harvard-CMT, id# 200605262253A, date 26 May 2006 22:54:5.3 GMT, Lat = −8.03, Lon = 110.54, Depth = 21.7, Mrr = −1.220, Mss = −3.360, Mee = 4.570, Mrs = 0.600, Mre = 0.623, Mse = 1.130, Mw = 6.4, NP1: strike = 323, dip = 77, slip = −176, NP2: strike = 232 dip = 86, slip = −13; http://www.globalcmt.org/CMTsearch.html). The information given by the U.S. National Earthquake Information Center Fast-Moment-Tensor (FMT) is M_w = 6.5, and

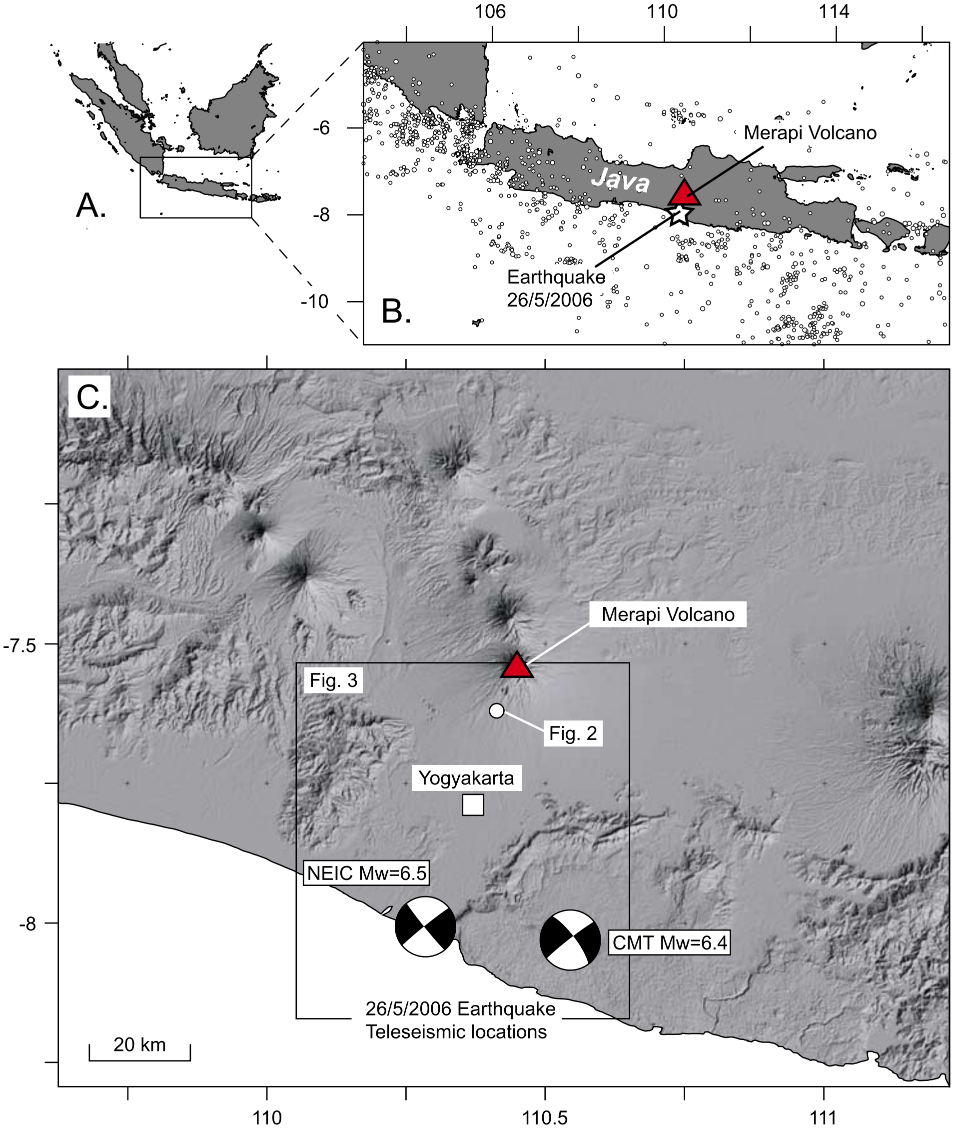

Figure 1. (a) Location map. (b) Merapi Volcano (red triangle) and the earthquake area on Java Island, Indonesia, with historical earthquake data shown by small black circles. (c) Shaded relief map of the Yogyakarta area, city center shown by white square symbol. The 26 May 2006 teleseismic locations and focal mechanisms are provided by National Earthquake Information Center (NEIC) and Harvard Centroid-Moment-Tensor (CMT). Circle indicates location of Figure 2 photographs; inserted box indicates map view dimensions in Figure 3.

shows the earthquake to be on the southern section of the Opak River Fault (NEIC, id# 0605262254, date 26 May 2006 22:54:1.18, Lat = –8.007, Lon = 110.286, Depth = 28, Mrr = 1.12, Mtt = –7.72, Mff = 6.63, Mrt = –0.13, Mrf = –0.41, Mtf = 1.47, MW 6.5, NP1: strike = 141, dip = 87, slip = 177, NP2: strike = 231, dip = 87, slip = 3, http://earthquake.usgs.gov/eqcenter/eqinthenews/2006/usneb6/, http://neic.usgs.gov/neis/eq_depot/2006/, 2007). Therefore, the NEIC FMT location apparently confirms the suspected Opak River Fault as the most likely earthquake source.

3. Temporary Network of the German Task Force for Earthquakes

[5] In order to record the aftershock activity, a rapid response team of the German Task Force for Earthquakes (GTF), together with the Seismological Division of Badan Meterologi & Geofisika (BMG)

Figure 2. Example of a lahar deposition zone on the south flank of Merapi volcano, photographed at the Boyong River Bridge at three months time distance (courtesy of F. Lavigne). (a) Land-used flanks of the valley in December 1994. (b) Volcaniclastic sediment deposition photographed in February 1995. This example illustrates the fast sedimentation rates and deposition of unconsolidated volcaniclastic material, the sites of which may be especially dangerous during an earthquake. For more details about this site see *Lavigne et al.* [2000].

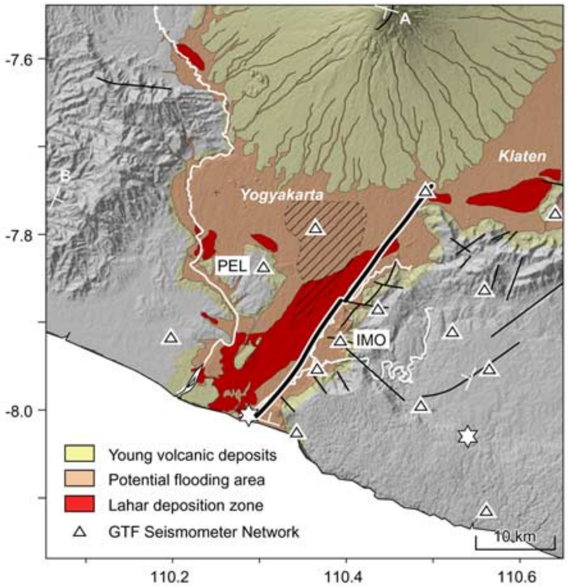

Figure 3. Shaded relief map of the area of Yogyakarta area, with Mt. Merapi Volcano in the north and Yogyakarta City in the center (dashed area). The thick black NE-SW trending line is the Opak River Fault, thought to be the source of the May 2006 earthquake disaster. Note that this is also bounding the region covered by young volcanic deposits [*Rahardjo et al.*, 1977] and the main distant deposition zone of lahars as suggested by *UNOSAT* [2006]. White triangles mark the temporary network of the seismic stations that were set up to record aftershocks, together with three-letter station codes for the stations further discussed in this paper. Teleseismic locations indicated by stars.

and the Gadjah Mada University (UGM) Yogyakarta set up the first seismometers on 31 May 2006. The network layout encompassed the earthquake disaster area along the Opak River Fault surrounding the area of expected aftershock activity (Figure 3). At the time of deployment, the exact location of the earthquake epicenter was not known. Moreover, since no primary surface ruptures allowed us to estimate the active fault, stations were arranged in order to cover a large area. On day 7 after the earthquake, the team had completed the set-up of a temporary network of 12 seismic stations (type Mark L4–3D 1 Hz and Earth Data Logger EDL). The average interstation distance was about 10 km, being smaller near the Opak River Fault (4 km) and larger at greater distances (16 km). The stations thus spanned an area of about 1,200 km^2 surrounding the earthquake destruction area in the district of Yogyakarta and recorded about 2,000 events within three months.

3.1. First Aftershock Location Results

[6] While the complete analysis of this unique data set has just barely begun, the study of the first 10% of the events (using the Hypo71PC program [*Lee and Lahr*, 1972] and a 1-D velocity layered crustal

Table 1. Double Couple Parameters for Nodal Plane 1 and 2 of the NEIC and Harvard Main Shock Solutions[a]

	Nodal Plane 1			Nodal Plane 2				
Name	Strike	Dip	Rake	Strike	Dip	Rake	Depth	Mag
NEIC	141	87	177	231	87	3	28.0	6.5
HRV	323	77	−176	232	86	−13	21.7	6.4

[a] HRV, Harvard; NEIC, National Earthquake Information Center. Both mechanisms suggest strike slip faulting but also have a CLVD component (not shown here). See for details Harvard-CMT (2007) and NEIC (2007).

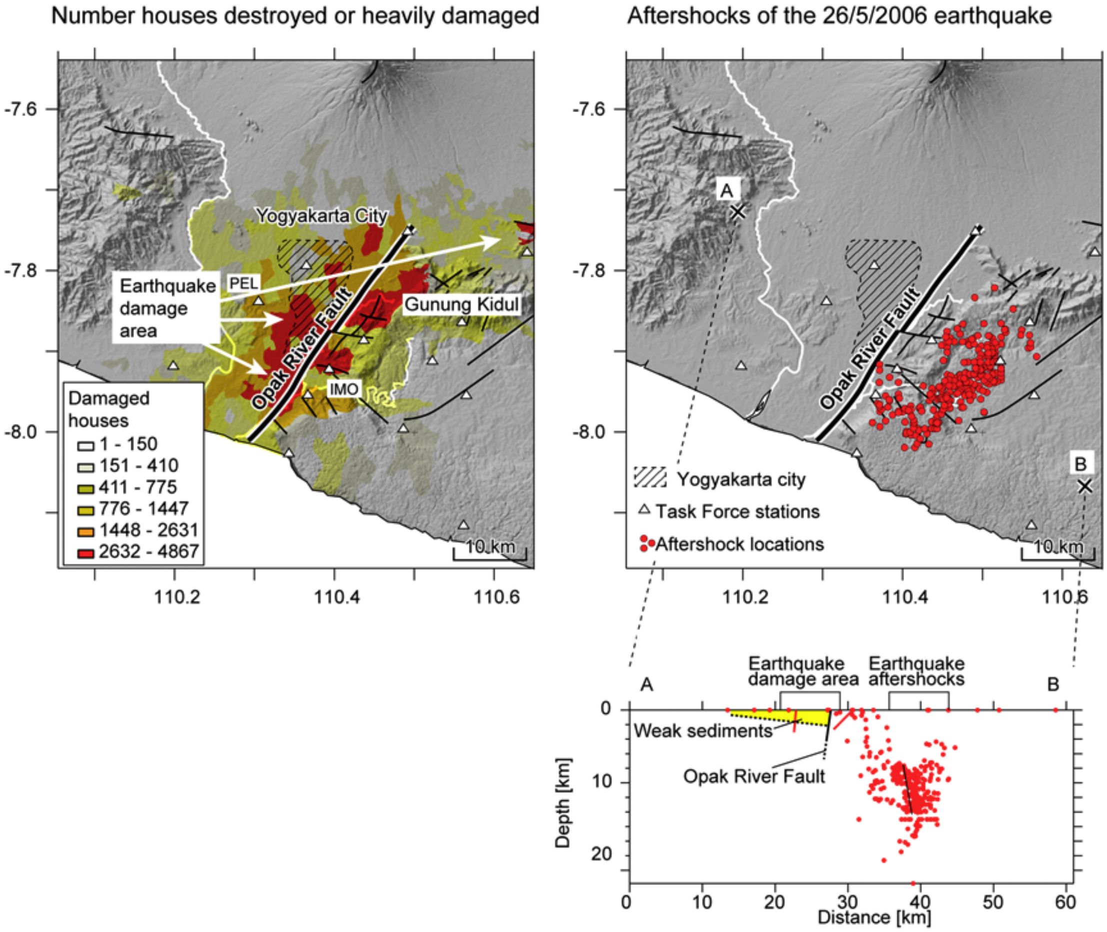

Figure 4. (left) Earthquake damage area and (right) aftershock locations. (left) Within the six most affected districts more than 35% of the total housing stock suffered damage [*UN Cluster Atlas*, 2007], being most severe along the Opak River Fault. The earthquake damage area is shown by the number of destroyed and heavily damaged houses within the affected villages [after *International Federation of Red Cross*, 2006; *UN Cluster Atlas*, 2007]. (right) First results of GTF aftershock localizations (red dots) show an event cloud 10–20 km to the east of the damage area. The cross section A-B shows the hypocenters of the aftershocks, the distance to the earthquake disaster area, and also the presence of volcanic sediments along the Opak River basin. Geologic structures (faults and sediment location) after *Rahardjo et al.* [1977].

model derived for the area by the MERAMEX seismic tomography project in the area [*Koulakov et al.*, 2007; *Wagner et al.*, 2007]) already provides important new insights in location and geometry of the earthquake rupture plane. The results surprisingly show that the aftershock hypocenters are not aligned along the Opak River Fault as originally thought, but rather at a hitherto unidentified fault 10–20 km further to the east, within the mountainous and less populated area of Gunung Kidul. Most of the aftershocks align in a northeast-southwest direction (N037°E), parallel to the Opak River Fault. About 90% of the data is along-strike within 19 km and across-strike within 4 km. Toward the northeastern and southwestern ends of the main aftershock cluster, the data appears to scatter spatially. The depth of the bulk of the aftershocks is at 8–15 km, the dip of the active fault appears to be subvertical, although further studies will be required to obtain more accurate information.

3.2. Local Amplification

[7] The private sector house stock was most heavily affected by the earthquake. About 160,000 houses were destroyed by the earthquake and another >250,000 damaged in the densely populated Yogyakarta area [*CGI*, 2006]. In comparison, the Aceh 12/26/2004 earthquake destroyed about 130,000 houses and damaged about 150,000. According to a report published by National Development Planning Board, and the provincial

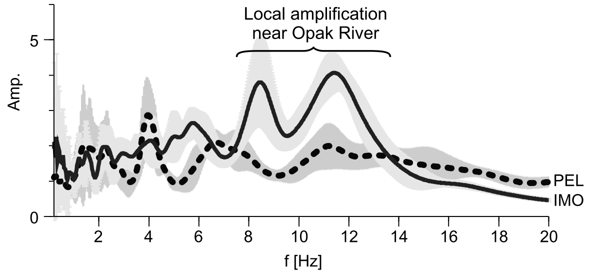

Figure 5. Frequency versus H/V amplitude compared at two GTF stations. Station PEL is located southeast of Yogyakarta City on bedrock in an area less affected by the earthquake, whereas station IMO is located in Imogiri, a village hardest hit by the earthquake (see also Figure 3). The frequency band implies that local amplification could have played a role at IMO, which is located near the Opak River, probably due to underlying soft sediments.

and local governments of Yogyakarta and central Java, more houses were affected in the Yogyakarta earthquake area than in Aceh and Nias after the 12/26/2004 and 03/28/2005 earthquakes combined [*Consultative Group on Indonesia*, 2006]. *Boen* [2006] observed that damaged or collapsed buildings were non-engineered constructions, mainly 1–2 story houses. Most of the destroyed houses were non-reinforced half or one brick thick masonry buildings held together with lime mortar of poor quality. The number of engineered buildings that collapsed is relatively small, where buildings with reinforced concrete structures showed often a damaged first soft story [*Boen*, 2006]. However, it was observed that some areas were more damaged than others, suggesting that local geological conditions might have also played a role in damage distribution. Areas of severe damage were found at Jetis, Imogiri, Sewon, Bantul, Prambanan in Sleman, Gantiwarno, and Wedi in Klaten.

[8] Assuming that the structure highlighted by the aftershock distribution indicates the location of the 26 May main shock, the question arises if the severe damage southeast of Yogyakarta city, previously explained as due to the vicinity to the Opak River fault, could have been instead resulted from site amplification.

[9] The seismic waveforms recorded by the GTF may provide further insights into this process. The recording of 9 aftershocks at station IMO (within the more damaged area) and station PEL (less damaged area) have been analyzed; both station locations highlighted in Figures 3 and 4. An S wave signal window was selected starting before the S wave arrival and ending when 90% of energy was reached. The Fourier spectra of the signal were calculated and smoothed using the Konno and Ohmachi window [*Konno and Ohmachi*, 1998]. We obtain the horizontal-to-vertical spectral ratio H/V [*Lermo and Chavez-Garcia*, 1993] after calculation of the root mean square (RMS) average of the horizontal components. The H/V spectral ratio allows us to estimate possible frequency dependent site amplification. A high degree of damage is expected if the fundamental frequency of the soil approaches the frequency of vibrating buildings. As shown in the average H/V spectral ratios of Figure 5, station PEL experienced small amplification whereas at station IMO significant amplifications are depicted in the frequency band of interest for 1–2 storey buildings (3–9 Hz), which can be estimated by the relation $1/f = (0.05 \times h)3/4$ where h is the height (in m) of the building [*Wiegel*, 1970].

[10] The reason for this site amplification may be explained as follows. Station IMO is located in an area that is defined to lie within the 2nd danger zone of Mt. Merapi volcano, meaning that it is not directly threatened by eruptions but may be invaded by lahars rich in clastic material in suspension [*Lavigne et al.*, 2000; *Rahardjo et al.*, 1977]. The deposited clastic material is generally soft, consisting breccias and pyroclastic deposits (tuffs, ash) reaching a thickness of 150–200 m [*Rahardjo et al.*, 1977]. The weathered and remobilized products of these deposits can be found in the plain to the south of Merapi. The H/V spectral ratio detected at station IMO may thus be related to the local presence of young volcanic deposits, that progressively infilled the tectonic graben bound by the Opak River Fault. Therefore, a role of site effects in increasing damage has to be considered in understanding the amount and distribution of damages due to the 26 May Yogyakarta earthquake.

3.3. Computer Simulation

[11] As shown above, the alignment of the recorded aftershocks correlates well with the rupture mechanism provided by the teleseismic moment tensor solutions (Harvard-CMT and NEIC; see section 2). In this section, we perform computer simulations in order to elucidate the distance between the damage area and the aftershock area. We assume that the aftershocks represent the fault of the M6.4 main shock, and consider a rupture plane with the center of the slip distribution being set to the center of the 20×10 km^2 aftershock area with its upper edge at 6 km depth. As rupture mecha-

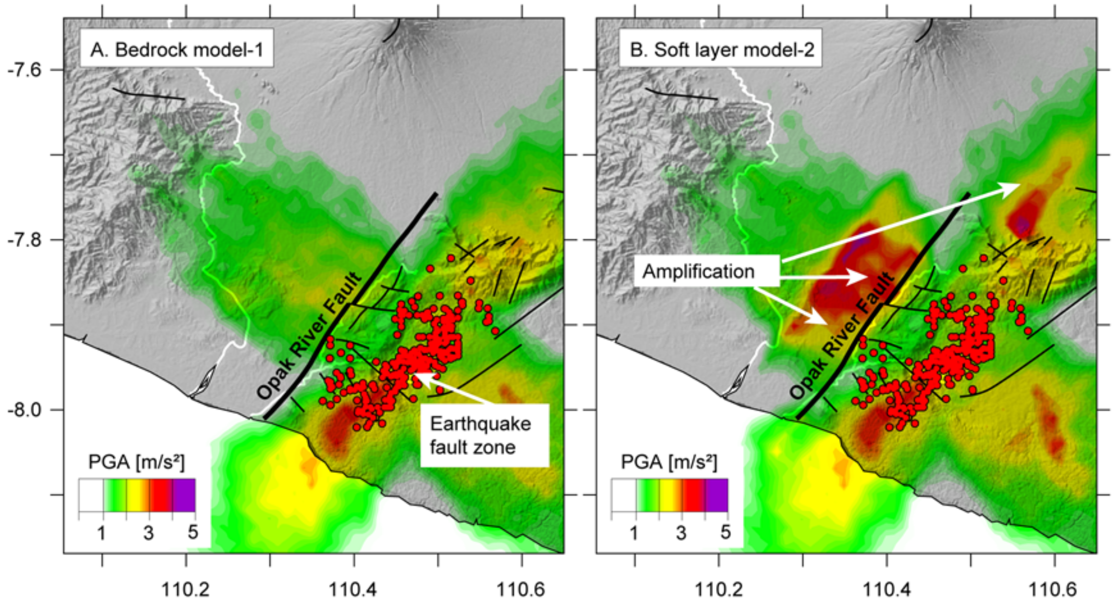

Figure 6. Shake maps. Computer models of the peak ground acceleration (PGA) induced by the 26 May 2006 M6.4 earthquake. Warmer colors indicate a larger PGA, calculated for (left) laterally homogeneous model (model-1) and (right) heterogeneous model with site effect (model-2) that considers soft sediments along the Opak River. Model that considers 150 m thick soft sediments along the Opak River suggests the highest acceleration in the zone of soft sediments, i.e., at 10–20 km distance from the aftershock region. The damage area well correlates with the distribution of PGA amplification.

nism we use the double-couple focal solution determined by Harvard (232°/86°/−13°). The rupture plane is divided into 2 × 2 km^2 source patches. A circular rupture front propagation is assumed, with a rupture velocity set to 2 km/s. We performed two types of models. In model 1, we define a laterally homogenous 1-D layered model. This model is hence considering stable bedrock, without any site effects. In model 2, we add a soft sedimentary cover along the Opak River. The 150 m thickness of the sedimentary cover was extrapolated from the published geological map [*Rahardjo et al.*, 1977]. First, we calculate synthetic seismograms for the bedrock model using the reflectivity method [see also *Müller*, 1985]. The site effect is then included by convolution between the bedrock synthetics and the transfer function of the local sediment cover. From the synthetic seismograms we derive the peak ground acceleration shown in Figure 6.

[12] We note that a stress drop on the active fault is not analyzed and that these models do not take into account topography or other complex lateral geometry effects. In addition, the models assume the sedimentary cover along the Opak River, from the coast until north of Gunung Kidul, that have a thickness = 150 m, a shear velocity = 500 m/s and a quality factor Q = 20. Even though the models are a simplification of a much more multifaceted geology, the results exemplify how the earthquake may have had a great destructive potential at 10–20 km distance to the rupture plane. In the area of highest damage, the peak ground acceleration is found to be about 200–300% larger than expected if underlain by stable bedrock. Our work illustrates an influence of the soft volcaniclastic sedimentary cover along the Opak River that significantly increased the destructive potential of the May 2006 Yogyakarta earthquake.

4. Discussion

[13] The May 2006 earthquake was one of the deadliest earthquakes in Java in historical times. Although the most recent magnitude estimations are only between 6.4 and 6.5 (Harvard-CMT and NEIC; see section 2), the scale of destruction is unprecedented in this region.

[14] In order to precisely measure and analyze the source, causes and effects of this earthquake, we installed a network of 12 temporary seismic stations, which recorded aftershocks for a duration of three months. The results presented in this study are revealing that the aftershocks are located in a region where no active fault was previously iden-

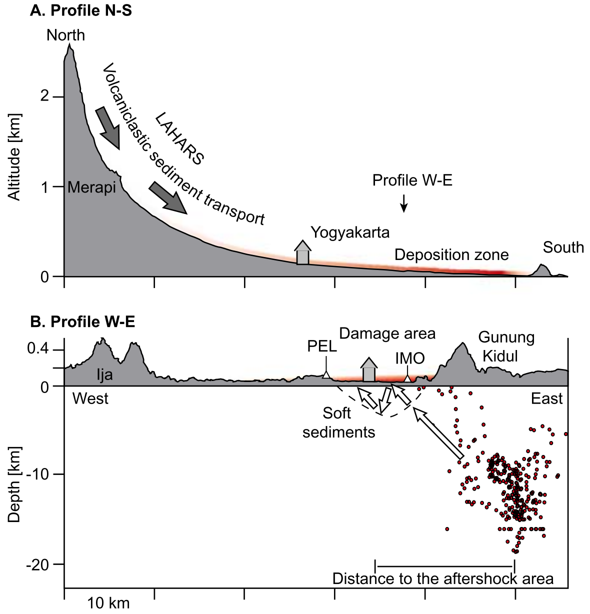

Figure 7. Sketch illustrating how lahar deposits may lead to earthquake disaster. (a) North-south profile, Merapi volcano to the north (left), zone of lahar deposition in the lowland plain to the south (right). Lahar deposition zone is indicated by red color. (b) East-west profile showing Ija Mountains to the west (left) and Gunung Kidul Mountains to the east (right). The Yogyakarta damage area (shown by house symbol), located in the lowland plain flanked by the two mountains, is underlain by unconsolidated volcaniclastic deposits derived from Mt. Merapi Volcano. Aftershocks are shown below this profile by red dots. Profile locations A and B are indicated in Figure 3.

tified. Assuming that the aftershocks delineate the main fault rupture plane, the distance to the damage area is 10–20 km. While the NEIC FMT solution suggests the earthquake to be on the southern section of the Opak River Fault, the HRV solution suggests a location more to the northeast. In combination, the solutions may indicate also a more complex (e.g., northeasterly) rupture propagation, which would be in line with the non-double couple component indicated in updated earthquake mechanism estimations (Table 1).

[15] On the basis of H/V spectral ratio at selected stations, geological information of the substratum and our model simulations that consider a soft volcaniclastic layer, this study suggests that local amplification of the seismic waves had a significant influence leading to the disaster (Figure 7). The soft sediments are mainly redeposited and altered volcaniclastics originating from the active Mt. Merapi volcano to the north, with thicknesses that are thought to be greatest (~200 m) in the damage area near the Opak River [*Rahardjo et al.*, 1977]. Significant sediment deposition occurs because of the three main factors [*Lavigne and Thouret*, 2003]: (1) pyroclastic material with millions of cubic meters in volume that accumulate during volcanic active phases, (2) high rainfall intensity often exceeding 40 mm in 2 h during the rainy season, and (3) dense south-directed drainage pattern. Lahars along the Boyong River may deposit sediments exceeding annually 200,000 m^3/km^2 at sedimentation rates of more than 3 cm/min [*Lavigne and Thouret*, 2003]. The sediments in the basin are accordingly derived from pyroclastic flow and surge deposits, lava dome rockfalls and material along the rivers. Here, we used simplified parameters to consider the sediment mechanical properties as well as their thickness distribution.

[16] In our model calculations, we have set the quality factor (Q) of the soft cover equal to 20. This is a valid estimate accounting for both intrinsic attenuation and the scattering effect. Different Q values may slightly influence the resonance effect, especially for large sediment thicknesses. However, for the herein studied scenario of thin sediment cover, the site amplification is dominantly controlled by the seismic impedance contrast to the bedrock. Field observations also show that topographic effects may have had an important role, where for instance buildings along the topographic crest of the Gunung Kidul Mountains were heavily destroyed, while the region located directly above the aftershocks has suffered comparable moderate destruction [*CGI*, 2006; *UN Cluster Atlas*, 2007]. Future studies thus need to consider the three dimensional topographic effects, in order to better understand the geometric influence of basins and hills in the region, see also [*Ripperger et al.*, 2003]. Similarly, the three dimensional structure derived from local tomography studies [*Wagner et al.*, 2007] may improve localization, modeling and interpretation of both damage distribution and earthquake aftershocks. Nevertheless, this work demonstrates that the 1-D effects shown by the H/V spectral ratio already provide a first explanation of damage distribution in the Yogyakarta area.

[17] Although its relatively small energy release, the 26 May 2006 earthquake had therefore various distant effects: (1) the earthquake triggered increased volcanic activity at the 50 km distant Mt. Merapi Volcano, where the magma extrusion rate and the number of pyroclastic flows suddenly

tripled [*Walter et al.*, 2007a], and (2) the earthquake caused destruction at 10–20 km distance along the Opak River due to soil amplification (this work). Other even farther effects at volcanoes in east Java are currently debated [*Cyranoski*, 2007; *Harris and Ripepe*, 2007; *Manga*, 2007]. Thus, the Yogyakarta earthquake had destruction and triggering effects both at many kilometers distance. In summary, this work sheds some light onto the complex interdependency of the causes and effects in a seismically and volcanically active environment, and suggests the importance to link seismic and volcanic hazard evaluations.

5. Conclusions

[18] Although the destruction area and the known fault traces suggested that the 26 May 2006 earthquake occurred along the Opak River Fault, our study points toward a hitherto unknown fault at about 10–20 km distance to the east. This work emphasized the effects of soft volcaniclastic lahar deposits along the Opak River and that the damage was mainly concentrated in an area where large amplification of ground motion might have occurred.

Acknowledgments

[19] Our special thanks go to our colleagues and collaborators in Indonesia who made this fast response possible. Andrea Heyn, Counsellor for Science, Technology and Environment at the German Embassy in Jakarta was of great help for logistical support. The proximal lahar deposition photographs were kindly provided by Franck Lavigne. We appreciated very detailed and constructive comments by G-Cubed editors and reviewers. Continuous financial support for Task Force field missions by Hannover Re is greatly acknowledged.

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