Bull Volcanol (2009) 71:845–857
DOI 10.1007/s00445-009-0268-8

RESEARCH ARTICLE

Extreme rainfall-induced lahars and dike breaching, 30 November 2006, Mayon Volcano, Philippines

**E. M. R. Paguican · A. M. F. Lagmay · K. S. Rodolfo ·
R. S. Rodolfo · A. M. P. Tengonciang · M. R. Lapus ·
E. G. Baliatan · E. C. Obille Jr.**

Received: 23 October 2007 / Accepted: 20 January 2009 / Published online: 24 February 2009

Abstract On 29–30 November 2006, heavy rains from Supertyphoon Durian remobilized volcanic debris on the southern and eastern slopes of Mount Mayon, generating major lahars that caused severe loss of life and property in downstream communities. The nearby Legaspi City weather station recorded 495.8 mm of rainfall over 1.5 days at rates as high as 47.5 mm/h, far exceeding the initiation threshold for Mayon lahars. For about 18 h, floods and lahars from the intense and prolonged rainfall overtopped river bends, breaching six dikes through which they created new paths, buried downstream communities in thick, widespread deposits, and caused most of the 1,266 fatalities. In order to mitigate damage from future lahars, the deposits were described and analyzed for clues to their generation and impact on structures and people. Post-disaster maps were generated from raw ASTER and SPOT images, using automated density slicing to characterize lahar deposits, flooded areas, croplands, and urbanized areas. Fieldwork was undertaken to check the accuracy of the maps, especially at the edges of the lahar deposits, and to measure the deposit thicknesses. The Durian event was exceptional in terms of rainfall intensity, but the dikes eventually failed because they were designed and built according to flood specifications, not to withstand major lahars.

Keywords Supertyphoon Durian (Reming) · Mayon Volcano · Lahar · Dike breaching · Rainfall · ASTER · SPOT

Editorial responsibility: J. White.

E. M. R. Paguican (✉) · A. M. F. Lagmay · K. S. Rodolfo ·
R. S. Rodolfo · M. R. Lapus · E. G. Baliatan
National Institute of Geological Sciences, College of Science,
University of the Philippines, Diliman,
Quezon City 1101, Philippines
e-mail: engiellepaguican@gmail.com

K. S. Rodolfo
Department of Earth and Environmental Sciences,
University of Illinois at Chicago,
845 W. Taylor St.,
Chicago, IL 60607, USA

A. M. F. Lagmay · K. S. Rodolfo · A. M. P. Tengonciang ·
M. R. Lapus
Earthprobe Incorporated,
P. Guevarra,
San Juan, Metro Manila, Philippines

A. M. P. Tengonciang
Department of Physical Sciences, College of Science,
University of the Philippines,
Governor Pack Road,
Baguio City 2600, Philippines

E. C. Obille Jr.
National Institute for Science and Mathematics Education,
University of the Philippines, Diliman,
Quezon City 1101, Philippines

Introduction

On 29 November 2006, Supertyphoon Durian (Philippine code name Reming), with maximum sustained winds of 190 km/hr and gusts as high as 230 km/hr, made landfall on the southeast coast of the Philippine island of Luzon, delivering 495.8 mm of rain over a period of 36 hrs (PAGASA 2006). Its impact was greatest in Albay Province, where runoff from its rainfall remobilized volcanic debris on the slopes of Mount Mayon into lahars that caused severe loss of life and property in downstream communities. Fatalities totaled 1,266, including 740 people missing and presumed dead (Rabonza 2006).

In terms of their volumes, runout lengths and devastative effects, the lahars of typhoon Durian are unprecedented in the recent history of Mayon. The closest event generating this magnitude of death and destruction on the lower slopes of Mayon was the 1825 lahar event that caused 1,500 fatalities (Task Group for the International Decade of Natural Disaster Reduction 1990) and buried the town of Cagsawa, 11 km southeast of the summit, 11 years after one of Mayon's largest eruptions during the 19th century (Ramos-Villarta et al. 1985). The November 2006 lahars followed a relatively minor effusive episode earlier in the year. This study describes and analyzes the deposits left by the lahars of typhoon Durian in order to understand the factors governing their generation and destructive impact. It is hoped that the descriptive accounts and analyses will aid in planning and design to mitigate future losses from lahars at Mayon and other volcanoes.

Mount Mayon

Mayon Volcano is a composite cone of andesite and basaltic-andesite lavas with associated pyroclastic-flow and lahar deposits (Newhall 1977, 1979; Punongbayan and Ruelo 1985; Rodolfo and Arguden 1991). It is very active; its latest eruption on 14 July 2006 was the 48th since records were first kept in 1616 (Ramos-Villarta et al. 1985; Philippine Institute of Volcanology and Seismology 2008). During many of Mayon's eruptions, heavy rains from storms or from eruption updrafts of moist surface air generate lahars on its slopes (Rodolfo 1989). Even during quiescent periods, monsoonal and typhoon rains of sufficient intensity and duration can mobilize debris into lahars. Typical major rain lahars, such as the one triggered by Typhoon Rosing 2 years after the 1993 eruption, last from several hours to 2 days and are mainly hyperconcentrated streamflows with interspersed debris-flow pulses with velocities of 3–6 m/s that each lasts several minutes to an hour (Arguden and Rodolfo 1990; Rodolfo and Arguden 1991).

The extraordinary symmetry of Mayon (Figs. 1 and 2) signifies that all radial sectors are equally affected by aggradational and degradational processes over the long term. In the short term, however, activity is far from even. Limited volumes of lava add only one or two narrow, radial tongues to the edifice; pyroclastic flows and lahars leave large, discrete deposits. During quiescent periods, erosional and depositional processes vary significantly between areas, and even between closely spaced channels.

Methodology

Remote-sensing data

Prior to field work, raw pre- and post-disaster Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and panchromatic SPOT 5 imageries, dated 15 December 2006 and 3 May 2006 respectively, were processed using ERDAS Imagine® software to generate a post-disaster map (Fig. 1). Flooded areas, croplands, and urbanized lands were classified through automated density slicing. Supervised (automated) classification of the lahar

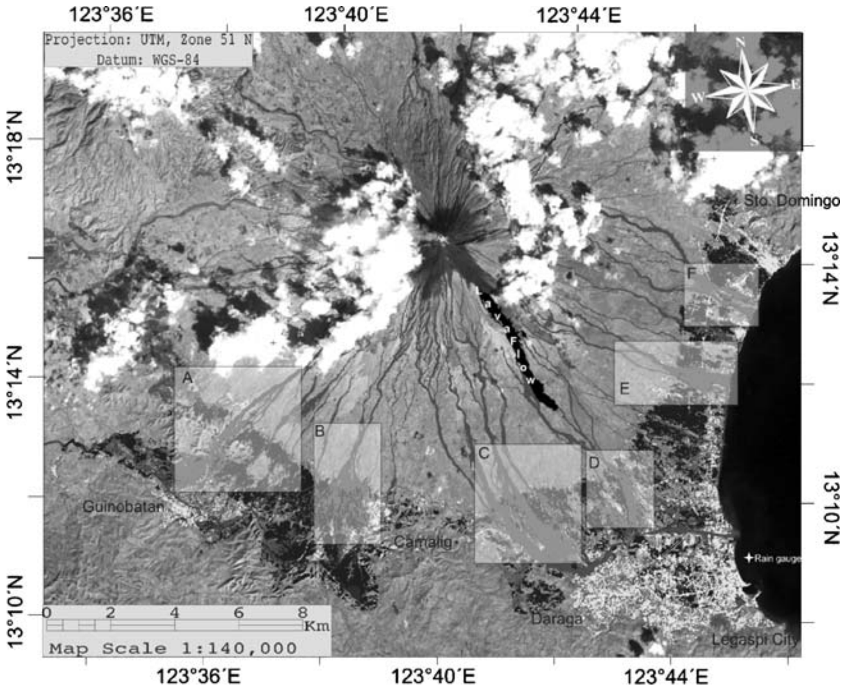


Fig. 1 Drainages and fresh lahar deposits (*50% black*) at Mayon volcano. Flood-prone areas are shown as *90% black*; urban areas as *10% black*. *Boxes A*, *B*, *C*, *D*, *E* and *F* are the locations of schematic diagrams A to F in Fig. 11. The base map is a 15 December 2006 ASTER image of Mount Mayon

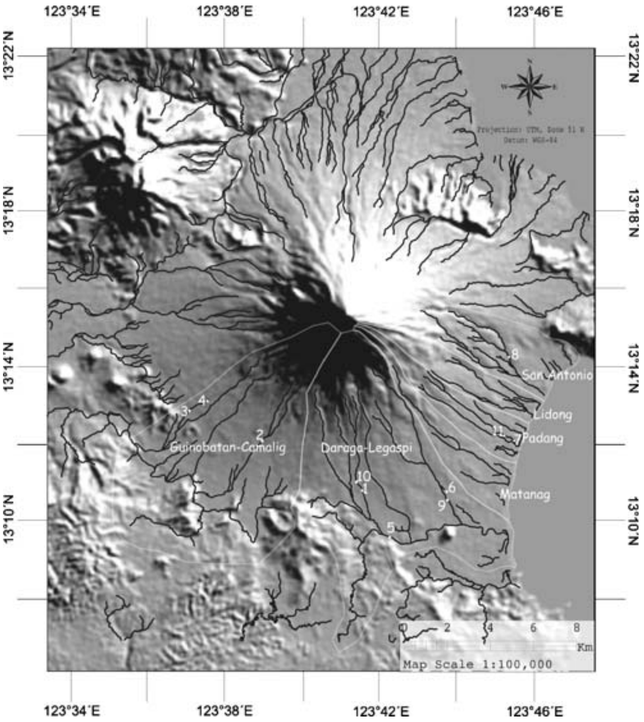


Fig. 2 The southern and eastern catchments of Mayon volcano. The *white numbers* are the locations of the 11 granulometric samples in Fig. 6a, b

deposits was not possible because they appeared too similar to flooded crop lands. Instead, the lahar deposits and drainages were manually delineated based on their areal distributions and associations with channels. Concrete dikes constructed along major channels around Mayon were delineated as light-colored linear features (Fig. 3a) in both radar and optical (Fig. 3b) imageries. Maps at a scale of 1:25,000 were validated in the field using hand-held Global Positioning System (GPS) instruments.

Field mapping

The lahar deposits were mapped in detail at communities with recorded casualties, all of which lay on the southern and eastern slopes of the volcano: Barangays (villages) Maipon and Tandarora in Guinobatan municipality, Sua in Camalig municipality, Budiao and Busay in Daraga municipality, Pawa and Padang in Legaspi City and San Antonio in Sto. Domingo municipality (Figs. 1 and 11; Table 1). Deposit thicknesses were measured along the margins of the deposit fields and across them to determine the volume of the lahar deposits. Stretches of constructed dikes were traced using hand-held GPS and parts where it was overtopped by lahar deposits and breached were noted.

Grain-size analysis

The fine-grained contents of lahars greatly influence their flow behaviors (Hampton 1975; Middleton and Hampton 1976; Qian et al. 1980; Costa 1984; Pierson and Costa 1987), and to determine their contents in the Durian lahars, matrices of seven debris-flow deposits and four hyper-concentrated-flow deposits were sampled (Fig. 2). One kg samples were oven-dried and cone-and quartered to obtain a subsample for granulometric analysis, which was passed through a stack of 2,000 μ and 62 μ sieves. To determine the clay fraction, subsample of five g except for Sample 4, were subjected to the pipette analysis recommended by Lewis and McConchie (1994).

Rainfall

The Philippine Atmospheric Geophysical and Astronomical Services (PAGASA) weather-monitoring station closest to Mayon is at Legaspi City, Albay, 12 km to the southeast of the volcano summit, and only 10 m above sea level.

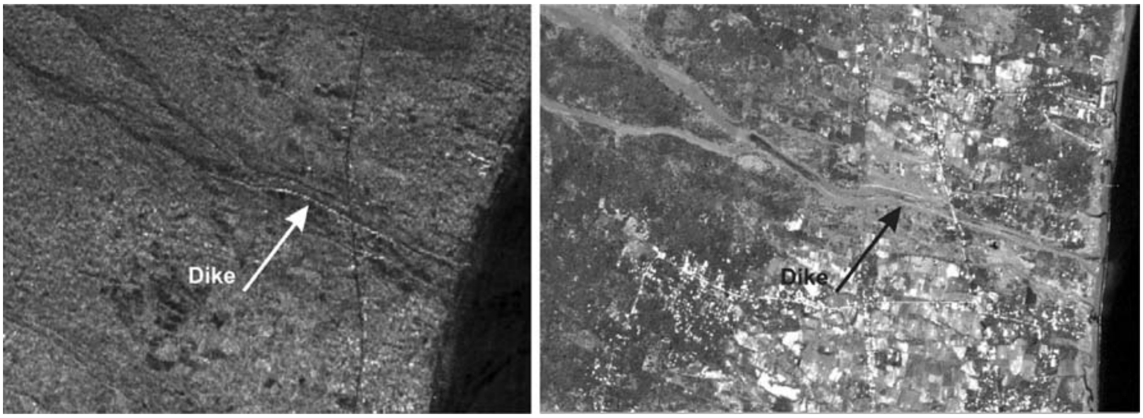


Fig. 3 Concrete dikes appear as light-colored linear features on both radar (**a**) and optical (**b**) images

Table 1 Casualties in barangays of five municipalities on the eastern and southern flanks of Mayon volcano

Statistics of typhoon Durian in five heavily affected municipalities

Settlement	Latitude	Longitude	Elevation (m asl)	Census year	Population	Houses		Barangays recorded deaths	Casualties
	Central (UTM Zone 51 N, WGS-84)					Totally damaged	Substantially destroyed		
Legaspi City	13.152162	123.735098	20	2007	194,580	12,095	18,636	Data not available	
Guinobatan	13.190602	123.600567	80	2000	71,071	5,291	7,196	Maipon	82
								San Rafael	22
								Tandarora	13
								San Francisco	10
								Minto	7
								Maguiron	3
								Masarawag	2
								Morera	1
								Iraya	1
								Travesia	1
Camalig	13.179444	123.654853	215	2003	60,280	7,386	6,406	Bariw	8
								Tinago	6
								Sumlang	4
								Sua	3
								Ilawod	2
								Cotmon	2
								Cabangan	2
								Balanog	1
								Quitinday	1
								Caguiba	1
Daraga	13.150491	123.709801	120	2006	6,664	8,544	9,833	Busay	57
								Bañag	26
								Budiao	8
								Tagas	5
								Binitayan	5
								Malabog	3
								Cullat	1
Sto. Domingo	13.235914	123.776751	35	2000	27,392	3,855	3,106	San Isidro	14
								Buhatan	7
								Alimsog	4
								Lidong	4
								Nagsiya	1
								Fidel Surtida	1

Records of rainfall, taken every 6 h using an 8-in. diameter standard manual rain gauge, were recovered in order to establish lahar-triggering intensities and durations.

Results

Remote-sensing

The southern and eastern sectors of Mayon's edifice comprise the catchments of Guinobatan–Camalig (67×10^6 m^2), Daraga–Legaspi (74.2×10^6 m^2), Matanag (14×10^6 m^2), Padang (10.6×10^6 m^2), Lidong (12.7×10^6 m^2) and San Antonio (20.0×10^6 m^2) rivers (Fig. 2). After Typhoon Durian, these radial channels now terminate in new lahar deposits that form debris fans on the volcano apron, extending downward along gradients of 5.5°–2.0° from elevations of about 245 to 100 m. Lahars along the Matanag, Padang, Lidong and San Antonio catchments reached Albay Gulf (Figs. 1 and 2). New channels formed by avulsion from pre-disaster gullies served as alternative pathways for these lahars.

Ricefields and coconut groves lying between drainage channels on the lower and gentler slopes of the volcano were heavily inundated (Fig. 1). Spectral reflectance of flood water and fresh lahar deposits are very similar in the 2006 ASTER image because their water contents made both appear as dark pixels, and to distinguish between the new lahar fields and croplands, lahar-deposit margins in the image were verified by field mapping (Fig. 5b).

Developed areas are situated mainly on the lower slopes of the volcano, 8–14 km from the summit. The largest communities are the cities of Legaspi and Tabaco and the municipalities of Guinobatan, Camalig, Daraga and Sto Domingo. Few barangays are situated on higher slopes, but can be as high as 400–500 m above sea level, 5 km from Mayon's peak (Fig. 1; Table 1).

Deposit characteristics, thickness and volume

The material remobilized into the lahars was dominated by old pyroclastic-flow and lahar deposits, with lesser volumes of tephra-fall material. Lahars flowing down the Matanag gully may have included lava fragments from the 1993 and 2001 eruptions. Bonga and Mabinit channels contain fragments from the lava deposited in 2006. Materials were incorporated into lahars above 100 m elevation in the eastern sector and above 200 to 245 m in the southern and southwestern sectors. In addition, materials scoured during the formation of new channels contributed to the lahar deposits.

The new lahar deposits, dark-colored and with the basaltic to andesitic compositions of Mayon's eruptive products, occur as two sedimentologic types. The first type is composed of poorly sorted clasts in sandy matrices (Fig. 5a). Clasts are sub-angular to rounded and vary in size from 1 cm to 3 m, with typical diameters from 8 to 25 cm. The matrix is composed of coarse (0.5–1 mm) to very coarse (1–2 mm) sand with only minor silt and clay fractions ranging from 2.75 to 10.8 wt.% (Fig. 6a). Overall textures are chaotic, as is typical for deposits of debris flows. Larger clasts commonly occur as scattered boulders on the surface of the deposit, as are typically lifted there by varying combinations of frictional, buoyant, dispersive, turbulent, and cohesive forces (Bagnold 1954; Hampton 1975, 1979; Pierson 1981; Phillips and Davies 1991; Major and Pierson 1992).

Deposits of the second type consist mainly of coarse to very coarse sand without large clasts and minor silt and sand fraction of 1.9 to 8.53 wt.% (Fig. 6a, b). They are massive or very crudely bedded, and are interpreted to have been deposited by hyperconcentrated flows. In the remotely sensed imageries, the debris-flow deposits correspond to the fan-shaped structures, whereas hyperconcentrated-flow deposits extend beyond the lahar fans and occur in distal portions of the channels.

Percentages of fine fractions are important regulators of lahar flow (Hampton 1975; Middleton and Hampton 1976; Qian et al. 1980; Costa 1984; Pierson and Costa 1987). Figure 6a shows that there is little clay-sized material in the lahars at Mayon, contributing to their non-cohesiveness. Clay fractions are randomly distributed in both debris-flow and hyperconcentrated-flow deposits.

The lahar deposits are thickest along their medial axes and thin to less than 0.5 m along their fringes (Fig. 5b). Average thicknesses were about 1.5 m, but in barangays Maipon and Busay maximum thickness are 3 m and 2.5 m respectively. Boulders and the coarsest particles in the lahar are segregated toward the surface (Figs. 4b, 8e, 9a and 12). These characteristics attest to some yield strength, as is characteristic for dense, non-Newtonian flows (Pierson and Scott 1985).

Measured areas and thicknesses yield a calculated total lahar deposit volume of about 1.87×10^7 m^3. Individual volumes along each channel in the Guinobatan–Camalig,

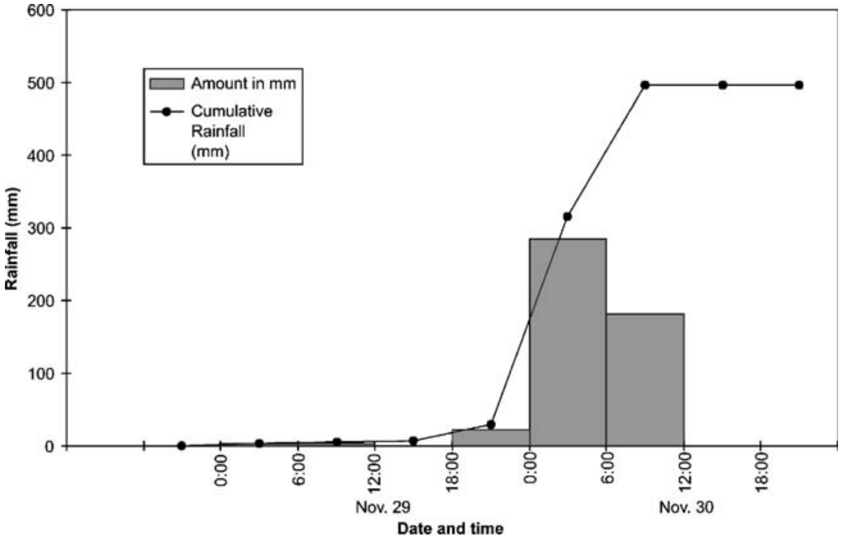


Fig. 4 Six-hour and cumulative rainfall recorded at the PAGASA weather station in Legaspi City on 29–30 November 2006

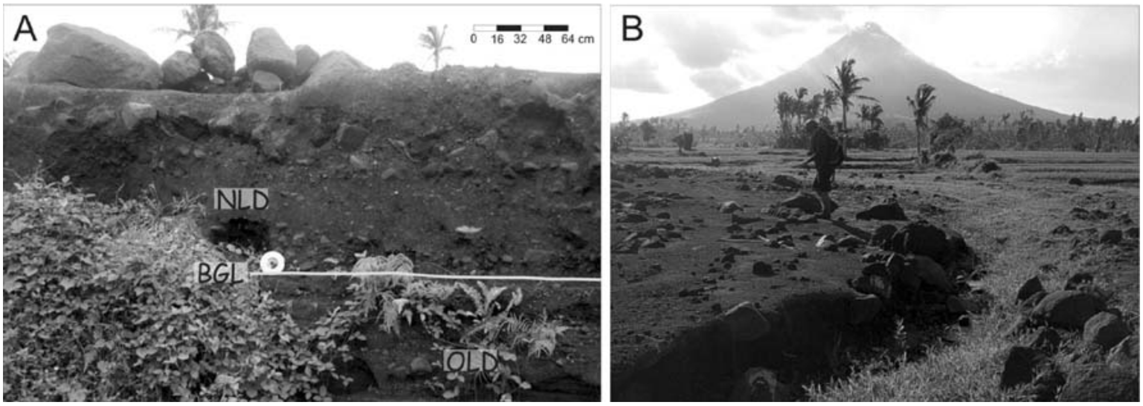


Fig. 5 **a** New lahar deposit (*NLD*) in profile view; *BGL* is the underlying buried grass line. **b** Edge of a lahar deposit about 0.5 m thick. Mayon volcano (summit elevation 2,462 m) is in the background

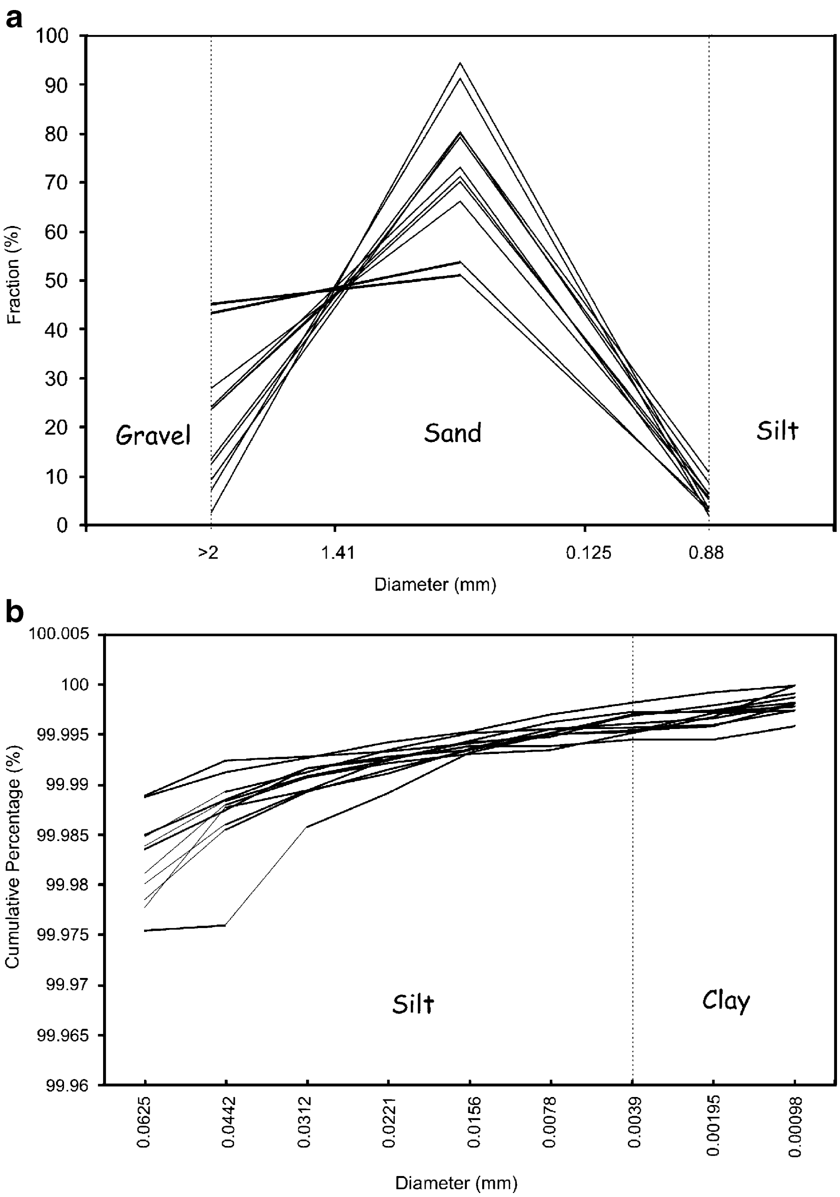


Fig. 6 Granulometry of 11 Typhoon Durian lahar samples from the eastern and southern flanks of Mt. Mayon. **a** Gravel, sand and silt + clay fractions; **b** cumulative distributions of silt and clay fractions. Sample locations are plotted in Fig. 2

Table 2 Calculated lahar volumes and deposit thicknesses exposed in gullies on the eastern and southern flanks of Mayon volcano

Volume calculation and deposit thickness

Area	Lahar deposit type	Max mapped thickness (m)	Min mapped thickness (m)	Volume (m^3)
Guinobatan–Camalig	Debris flow to hyperconcentrated flow	5.0	0.3	8,700,000
Daraga–Legaspi	Debris flow to hyperconcentrated flow	5.0	0.3	7,850,000
Padang	Debris flow to hyperconcentrated flow	1.6	0.1	850,000
Lidong	Debris flow to hyperconcentrated flow	1.5	0.2	300,000
San Antonio	Debris flow to hyperconcentrated flow	1.7	0.2	1,100,000
Total				18,800,000

Daraga–Legaspi, Matanag, Padang, Lidong, and San Antonio watersheds are listed in Table 2.

Dikes

Most of the protective engineering structures at Mayon, constructed with the financial assistance of the Japan International Cooperation Agency, are spur dikes and retaining walls two to three meters high, meant to channelize flows and reduce sediment load (Umbal 1986). Dikes were constructed out of old lahar deposits, overlain by boulder-sized sediments and secured in some areas by 2-cm diameter vertical steel bars covered with 4 to 7 cm of cement (Fig. 7). Some dikes, as in Basud gully, had no steel reinforcement. At six breaches, lahars left boulder-to sand-sized sediments atop the truncations (Figs. 8a–f and 11). According to local residents at Barangay Sua in Camalig, lahars there passed unobstructed above a sabo dam that had been filled up over the ten previous years, overtopping parts of the dike system downstream. Upstream of Basud gully, lahars widened channels by continuous lateral erosion of the river bank. Overtopping and deposition by lahars occurred on the outer bends of Basud (upstream) (Fig. 12), Guinobatan, Camalig, Daraga, Bonga and Padang gullies as well as the inner bends of Camalig and Basud (downstream) channels (Fig. 11).

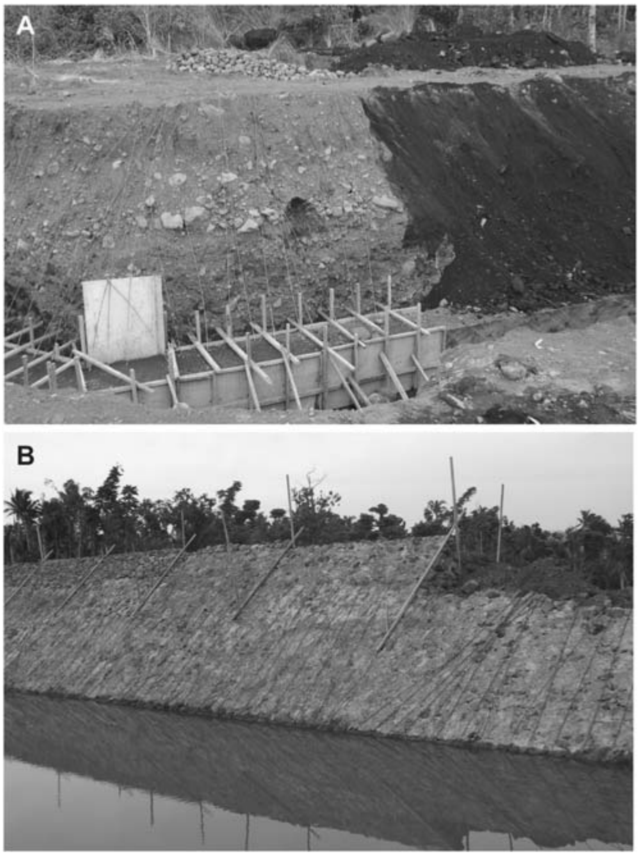


Fig. 7 Dikes in construction on major Mayon channels

Rainfall

At the Legaspi meteorologic station, the lahar-generating rain commenced during the 6-h period between 1800 H on 29 November and 0000H on 30 November, and ended during the 0600 H to 1200 H period of the 30th (Fig. 4). Very likely, the actual lahar-triggering rain on the volcano itself started sometime between midnight of 29 November and 0600H on 30 November. Over that approximately 18 h of record, the rainfall at Legaspi totalled 489.2 mm, equivalent to 2 months of normal rainy season precipitation, an amount unprecedented in the PAGASA data gathered since 1961. The previous maximum record was 484.6 mm, which fell during the 24-h period starting at 0800 H on 3 November 1967, 20 years after the 1947 eruption (Ramos-Villarta et al., 1986). No lahars were reported for that episode because loose pyroclastic debris that could potentially mobilize into lahars was either already stabilized, scarce, or had been depleted over the intervening two decades by background reworking.

Rainfall intensities measured at Legaspi during Typhoon Durian were as high as 47.5 mm/h. Doubtless, lahar-triggering rainfall on the volcano slopes was significantly higher and more intense because of orographic enhancement. Rodolfo and Arguden (1991) measured Mayon rainfall at sites 600 m above sea level from 1986 to 1988.

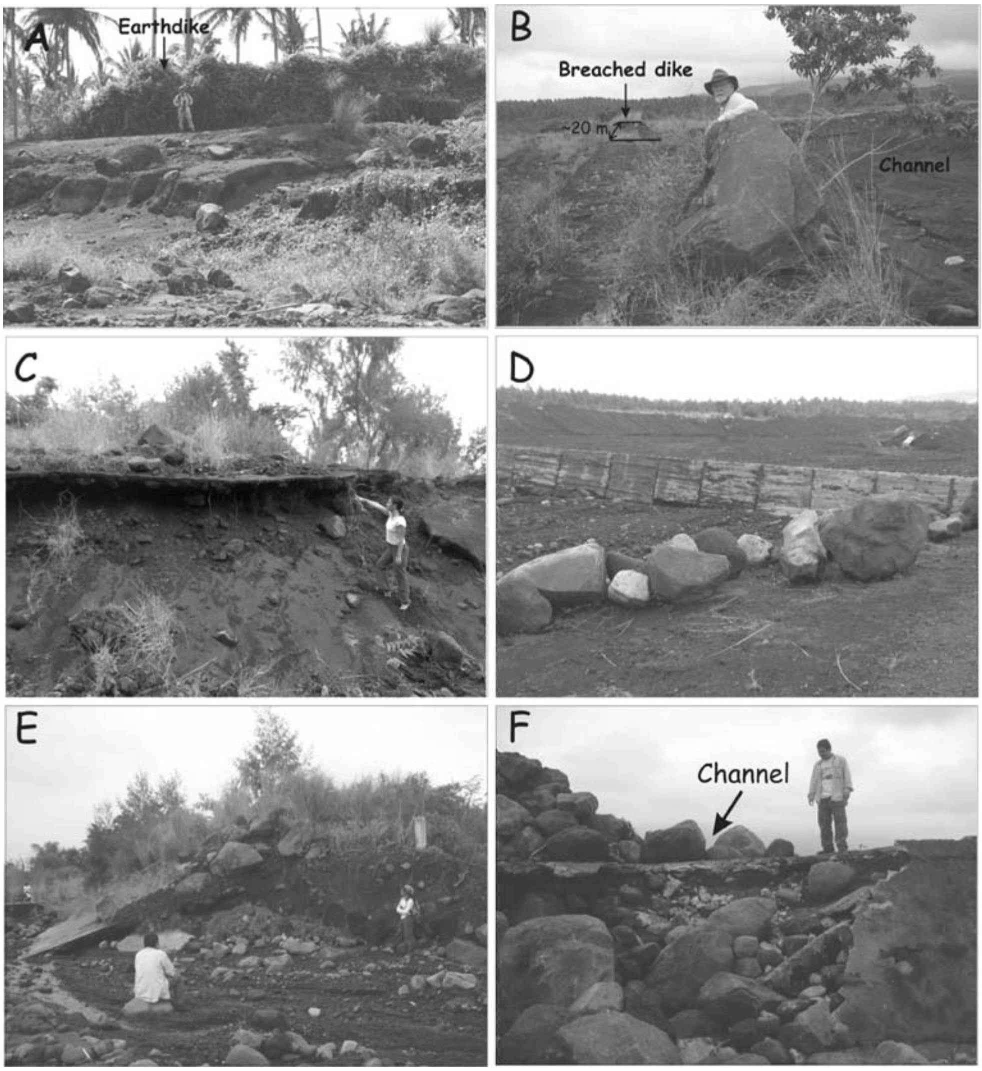


Fig. 8 Breached earth dike at Barangay Maipon in Guinobatan (**a**); overtopping at breached dikes in Barangay Sua in Camalig (**b**); upstream of Padang, Legaspi City (**c**); Sabo dam upstream of the breached dike in Sua, Camalig (**d**); upstream (**e**) and downstream (**f**) Basud Gully

Values during typhoons commonly were twice, and on one occasion even five times the values recorded at Legaspi.

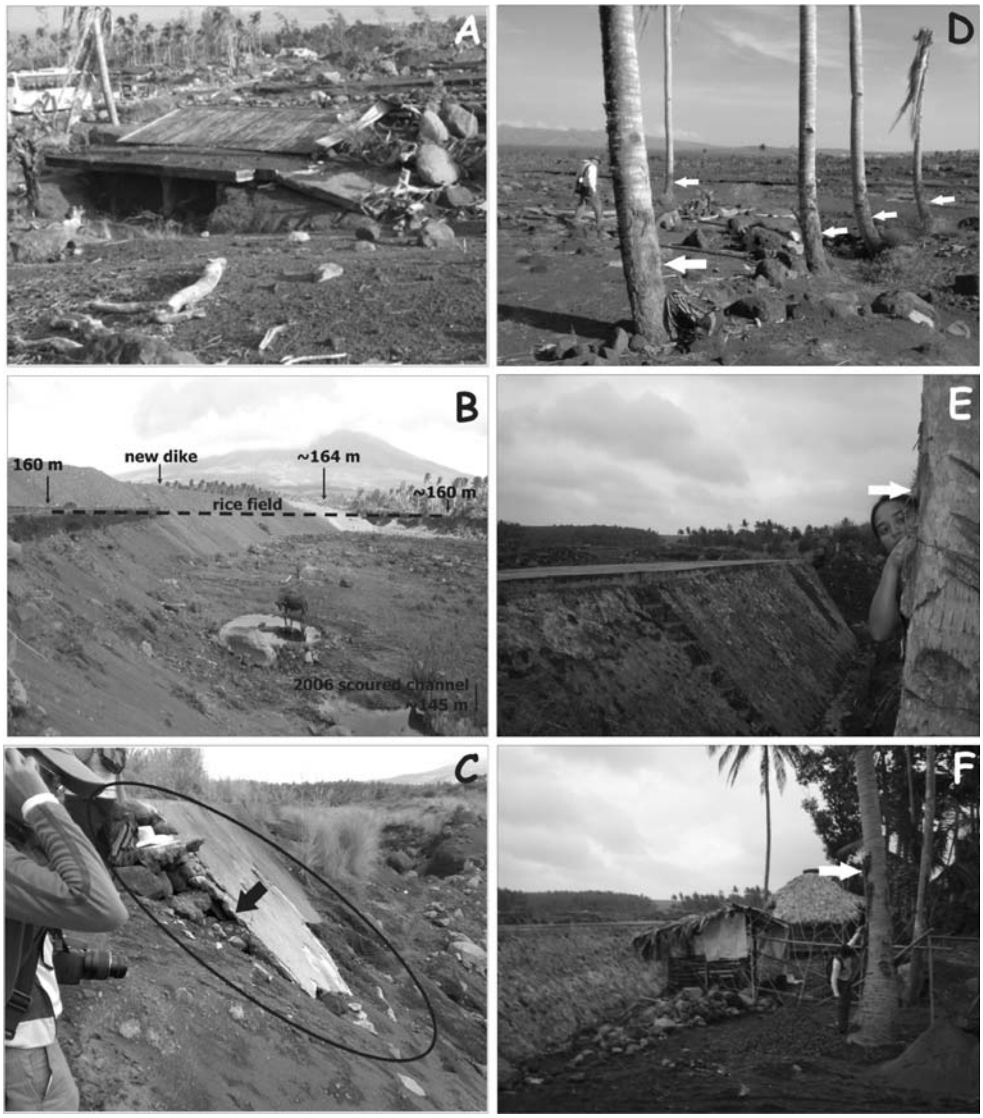
Impacts

The most important effect of the lahars was the toll of 1,266 deaths. According to eyewitnesses in all the barangays, the massive dense flows arrived suddenly at about 1400H on 30 November 2006 and subsided within a few minutes. After these brief surges, flood levels fell, but channelized flows were still vigorous. Carrying boulders up to 4 meters wide, lahars swept away people who were unable to reach higher ground. Lahars buried houses; among scattered, protruding rooftops, the barren fields are now strewn with large boulders (Fig. 9a). The portions of coconut trunks facing upstream were scarred up to a few meters above the surface of the lahar deposit, indicating the climax-stage heights of the lahars (Fig. 9d, e, f). Upstream of all the lahar ravaged communities, containment dikes were breached and new channels up to 100 m wide and 15 m deep were cut through rice fields, coconut plantations and settlements. Evidence for dike breaching include boulders atop truncated dikes, and coconut trunks immediately upstream of the breaches that were scarred by boulders at levels above dike tops (Fig. 8a, b, c, d, e, f).

Discussion

The characteristics, generation, and triggering mechanisms of Mayon lahars have been well studied (Rodolfo 1989; Arguden and Rodolfo 1990; Rodolfo and Arguden 1991) and have been used as basis of lahar studies elsewhere, including those at Pinatubo volcano (Arboleda and Martinez 1996; Tungol and Regalado 1996; Rodolfo et al. 1996; Umbal and Rodolfo 1996; Van Westen and Daag 2005). Lahars are continua ranging from more dilute hyperconcentrated flows to massive debris flows (Smith and Lowe 1991), which are initiated when site-specific thresholds defined by rainfall duration and intensity are exceeded. Relationships between rainfall intensity and distribution, and lahar initia-

Fig. 9 Lahar impacts. **a** Buried houses with scattered boulders. **b** Channel 80 m wide and 15 m deep that formed when the lahar-containment dike at Padang was breached. **c** Reconstructed breached dike in Barangay Sua, Camalig with a 20 m wide breach; the *arrow* indicates the thin armor of unreinforced concrete. **d**, **e**, **f** Scarred coconut trees (*white arrows*) facing upstream



tion have been investigated previously at Merapi Volcano, Central Java in Indonesia following its 1984 eruption (Sutikno and Sakatani 1993; Suwa and Sumaryono 1995; Lavigne et al. 2000a, b), and at Sakurajima (Daido 1985) and Yakedake volcanoes (Okunishi and Suwa 1985; Okunishi et al. 1988; Ikeya 1989) in Japan. In a study of 39 lahar-forming events by Rodolfo and Arguden (1991), the threshold of debris flow initiation was determined by an empirical relationship:

$$I = 27.3D^{-0.38}$$

where I is intensity and D the duration of rainfall. Compared to the worldwide intensity threshold values for debris flow generation (Balducci 2007), the triggering intensity for Mayon lahars is higher due to the coarse, granular, and very porous volcaniclastic surface material, which also renders the lahar-generating role of antecedent rain relatively insignificant (Rodolfo and Arguden 1991).

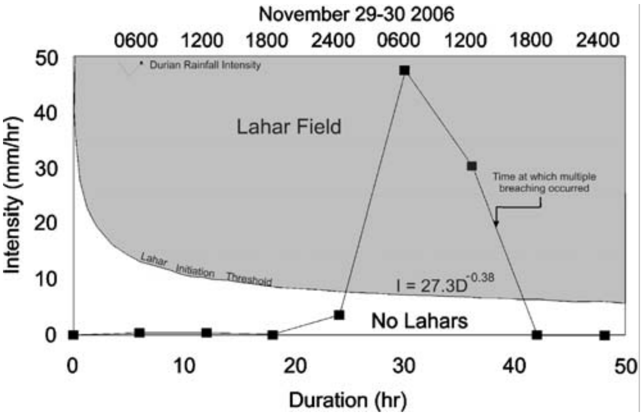


Fig. 10 Rainfall intensity-duration threshold for the generation of Mayon lahars (after Rodolfo and Arguden 1991), and the 6-h average intensities and duration during Typhoon Durian

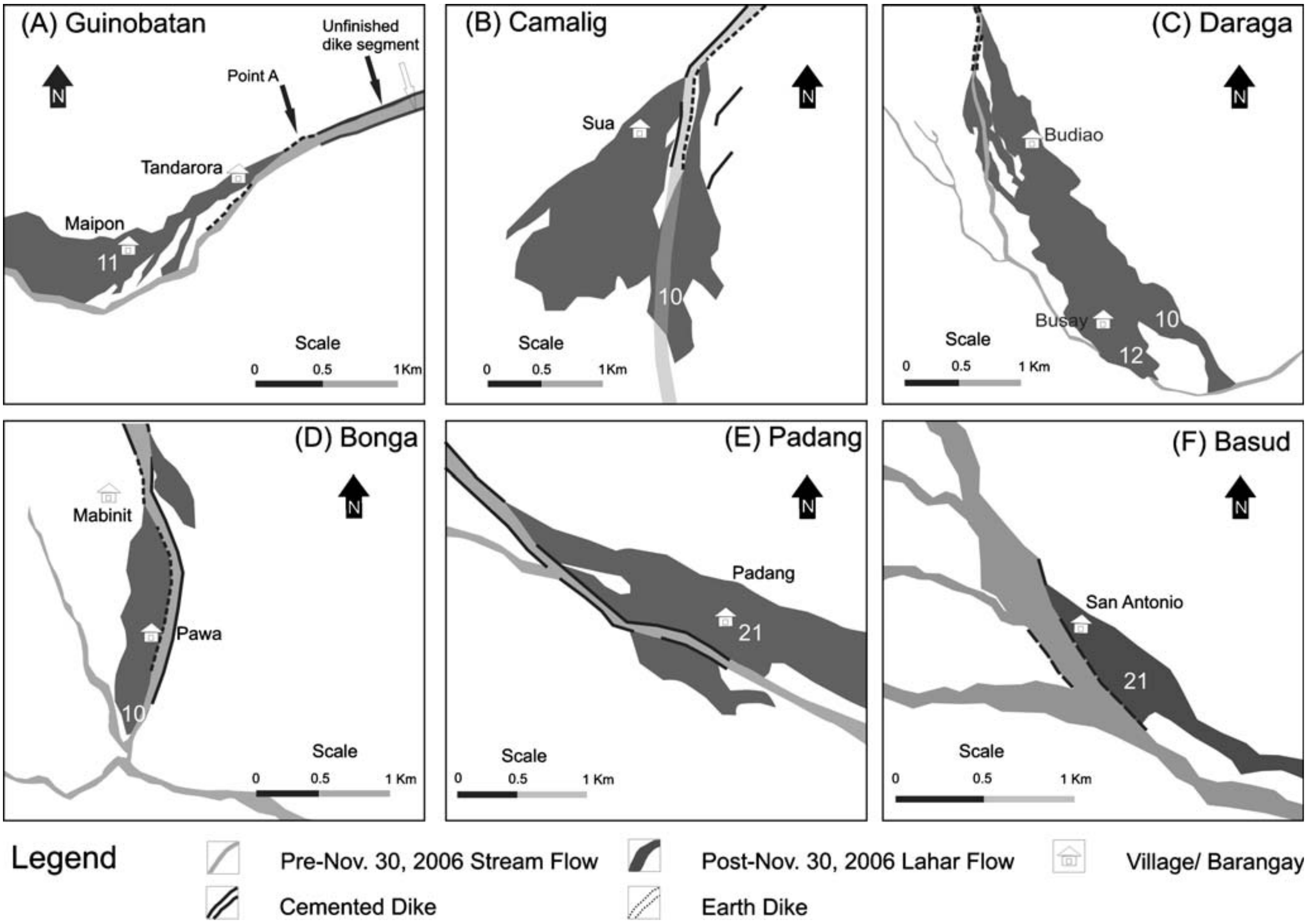


Fig. 11 Pre-30 November 2006 drainages, dike breaches and 2006 lahar deposits. The *white numbers* are minutes of travel time to each location after lahar initiation, calculated as a function of near-source flow rate and distance from source (from Pierson 1998)

Grain size is also strongly correlated with erosion rates, because fine-grained ash decreases surface permeability, increasing run-off (Segerstrom 1950; Waldron 1967; Collins and Dunne 1986; White 1991).

Plotted against the graph of the average intensity computed from the rainfall record of 29–30 November 2006 (Fig. 10), the equation shows that lahars probably started forming early on the morning of 30 November 2006 and were continuously generated until the early afternoon of 30 November 2006. Although it may be argued that the relationship of rainfall intensity and duration with lahar initiation threshold values is not linear from the time of an eruption but instead approximates a power law relation (Van Westen and Daag 2005), the rainfall intensity values from the evening of 29 November 2006 to noon of 30 November 2006 plot far in excess of the minimum threshold determined by the equation of Rodolfo and Arguden (1991).

According to local residents, all of the communities that were ravaged by lahars were hit by debris flows at around 1400H of 30 November. Barangays Tandarora, Maipon, Sua, Budiao, Busay, Mabinit, Pawa, Padang, and San Antonio were overrun by debris flows (Fig. 11), even though they were not beside or directly in the path of well-developed river channels. Lahar travel times were estimated (Fig. 11) as being a function of near-source flow rate and distance from source (Pierson 1998). Near-source peak discharge (Q_p) was estimated based on the deposit volume using the regression equation of Mitzuyama et al. (1992):

$$Q_p = 0.0135V^{0.780}$$

These yield travel times of 9 min for lahar discharge of 1,700 m^3/s to 22 min for a discharge of 218 m^3/s.

Field investigation of the upslope traces of some debris flows revealed breached sections of the dikes. In Sua, the breach was about 20 m wide, forming a channel 50 m wide and 7 m deep (Fig. 9c). A more striking example was the breached dike at Padang (Fig. 9b), through which an 80 m wide and 15 m deep channel was cut through rice paddies and coconut groves. Based on the timing of the arrival of debris flows at the communities, it would appear that dikes

Fig. 12 Eroded river bank along the outer bend of Basud channel, and overbank lahar deposits

all over the southern and eastern sectors of Mayon were breached at about 1400H, several hours after the first lahars were initiated.

However, upstream of Barangays Tandarora and Maipon in Guinobatan, the areas with the highest death toll, none of the existing concrete dikes breached. No evidence of overtopping was observed. Lahars that breached through the earthdike (Figs. 8a and 11) in Guinobatan, upslope of Barangays Tandarora and Maipon, created a new channel and inundated them. A portion of the pre-2006 river channel was transgressed along its bend (point A of Fig. 11a (Guinobatan)).

This same kind of lahar erosion along the inside bend of the river downstream occurred in Basud (Fig. 11f). On its upstream, boulders had begun to erode the outside bend portion of the river channel (Fig. 12), depositing material on the river bank as far as 7 m away from its margin. Trunks of coconut trees were scarred up to 1.6 m above the 0.6 m-thick overbank lahar deposits, through which a 1-m wide and 0.5-m deep stream channel was cut outwards from the main channel. It is not known, however, if this channel was formed as a result of the overflow along the river bend or whether it had already existed.

The lahars initially were confined in river channels by dikes that were later breached during peak flow. Possibly, as at Mount Pinatubo, debris flows overtopped banks both on the inside and outside of channel bends (Figs. 11 and 12), first eroding the outer, unarmored back sides of dikes until they collapsed, and creating new pathways for the flows to cut through fields and overrun settlements. Inasmuch as the lahars inundated all the barangays virtually at the same time, peak flows, surges, and eventual dike breachings must also have occurred just before this period. Like the 1984 lahar events, the large volume of material being transported immediately filled the dikes, thereby increasing the risk of spillover due to bed aggradation and the reduction of channel capacity. Dikes were constructed more than a decade before the 2006 lahars, and succeeding eruptions until the one in August 2006 may have invalidated previous lahar-vulnerability assessments around the volcano.

The drawbacks demonstrated by the construction of supposedly protective engineering structures around Mayon may be remedied by regular dredging or increasing the dimensions of these structures to accommodate succeeding flows, which are both costly. A cost-effective remedy is to have a lahar warning system based on rain-gauges or installation of an array of acoustic flow monitors on the lahar initiation zones. Vulnerability assessment of areas around Mayon must be repeated after eruptions and major lahar events. Given all the other volcanic hazards that may cause havoc to people living in the highly populated and urbanized areas in the shadow of Mt. Mayon, a long-term solution may be to slowly resettle them away from its flanks.

Summary

Over the period of only 1.5 days from 29–30 November 2006, supertyphoon Durian delivered extremely high amounts of rainfall to the southeastern and eastern sectors of Mayon volcano, far exceeding the initiation threshold for Mayon lahars and for debris flows worldwide. Lahars may have already been flowing early on the morning of 30 November, but at about 1400H on 30 November, major floods and lahars attained overbank discharges, overtopping river bends (Figs. 8b, c, d, e, f and 12), breaching dikes ostensibly built to contain rainstorm floods, and passing though the breaks to cut new paths through rice fields, coconut groves, and communities. Along their newly created paths, the lahars eroded deeply into older deposits, swelling with the incorporated material, which implies that lahars were relatively dilute and undercapacity while the main channels were aggrading. This suggests that the lahar were vertically stratified with a dilute upper part. The lahars rampaged through Sua in Camalig, Budiao and Busay in Daraga, and Bonga, Pawa and Padang in Legaspi City.

Most of the 1,266 recorded fatalities were amongst those who chose to stay in their homes, even after the government had offered them temporary evacuation shelters until the typhoon had passed. These deaths were caused by lahars that breached six dikes. If Fig. 9c is representative, the dikes are far too fragile to withstand debris flows. Even without overtopping, concrete armor only a few centimeters thick cannot withstand the impact of boulders rafted by lahars, or even logs flung against it by storm floods. It might be argued that the Durian event was exceptional, but containment structures must be built to withstand worst-case events. The dikes were able to contain the lahars in their channels for a prolonged period during the typhoon, but eventually failed along channel bends after about 18 h of continuous intense rainfall.

Acknowledgments This work was supported as part of the project, "*Monitoring the Impacts of Disaster Risk in Albay Province: Towards Risk-sensitive Development*" in collaboration with The Manila Observatory and The Luis A. Yulo Foundation for Sustainable Development and Christian Aid and Oxfam Great Britain, our funders. Cristina Remotigue, Catherine Abon, Christine Bellen and Margaret Louise Honrado provided invaluable field assistance. Finally, we acknowledge the careful editing of James DL White and the thorough reviews by Vernon Manville and Thomas Pierson.

References

Arboleda R, Martinez M (1996) 1992 lahars in the Pasig-Potrero River system. In: Newhall C, Punongbayan R (eds) Fire and mud: eruptions and lahars of Mount Pinatubo. Philippine Inst Volcanol Seismol, Quezon City, pp 1045–1052

Arguden AT, Rodolfo KS (1990) Sedimentologic and dynamic differences between hot and cold laharic debris flows of Mayon Volcano, Philippines. Geol Soc Am Bull 102:865–876

Bagnold RA (1954) Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear. Proc R Soc London Ser A 225:49–63

Balducci V (2007) Rainfall thresholds for the initiation of landslides. http://rainfallthresholds.irpi.cnr.it/credit.htm. Accessed September 23, 2007

Collins BD, Dunne T (1986) Erosion of tephra from the 1980 eruption of Mount St. Helens. Geol Soc Am Bull 97:896–905

Costa JE (1984) Physical geomorphology of debris flows. In: Costa JE, Fleisher PJ (eds) Developments and applications of geomorphology. Springer, Berlin, pp 269–317

Daido A (1985) Effect of volcanic ash on occurrence of mud-debris flows. In: Proceedings of International Symposium on erosion, debris flows and disaster prevention. Tsukuba, Toshinto Printers, pp 250–260

Hampton MA (1975) Competence in fine-grained debris flows. J Sed Petrol 45:834–844

Hampton MA (1979) Buoyancy in debris flows. J Sed Petrol 49:753–758

Ikeya H (1989) Debris flow and its countermeasures in Japan. Bull Int Assoc Eng 40:15–33

Lavigne F, Thouret JC, Voight B, Suwa H, Sumaryono A (2000a) Lahar at Merapi Volcano, Central Java: an overview. J Volcanol Geotherm Res 100:423–253

Lavigne F, Thouret JC, Voight B, Young K, Lahusen R, Marso J, Suwa H, Sumaryono A, Sayudi DS, Dejean M (2000b) Instrumental lahar monitoring at Merapi Volcano, Central Java, Indonesia. J Volcanol Geothermal Res 100:457–478

Lewis DW, McConchie D (1994) Analytical sedimentology. Chapman & Hall, New York

Major JJ, Pierson TC (1992) Debris flow rheology: experimental analysis of fine-grained slurries. Water Res Res 28:841–857

Middleton GV, Hampton MA (1976) Subaqueous sediment transport and deposition by sediment gravity flows. In: Stanley DJ, Swift DJP (eds) Marine sediment transport and environmental management. New York, Wiley, pp 197–218

Mitzuyama T, Kobashi S, Ou G (1992) Prediction of debris flow peak discharge. Proc Interprevent Int Symp (Bern) 4:99–108

Newhall CG (1977) Geology and petrology of Mayon Volcano (MS Thesis): Davis, California, University of California, 292 p

Newhall CG (1979) Temporal evolution of the lavas of Mayon Volcano, Southeastern Luzon, Philippines. J Volcanol Geothermal V 6:61–83

Okunishi K, Suwa H (1985) Hydrological approach to debris flow. In: Proceedings of the International Symposium on Erosion, Debris Flow and Disaster Prevention, pp 243–247

Okunishi K, Suwa H, Hamana S (1988) Hydrological controls of erosion and sediment transport in volcanic torrents. Hydrol Sci J 33:575–587

PAGASA (2006) Philippine Atmospheric Geophysical and Atmospheric Services Rainfall archive. Data record

Philippine Institute of Volcanology and Seismology (2008) Mayon Volcano. www.phivolcs.dost.gov.ph/Volcano/Volcanolist/mayon.htm. Accessed 11 February 2008

Phillips CJ, Davies TRH (1991) Determining rheological parameters of debris flow material. Geomorphology 4:101–110

Pierson TC (1981) Dominant particle support mechanism in debris flows at Mount Thomas, New Zealand and implications for flow mobility. Proc 1985 Geomorphol Symp 18:49–60

Pierson TC (1998) An empirical method for estimating travel times for wet volcanic mass flows. Bull Volcanol 60:98–109

Pierson TC, Costa JE (1987) A rheologic classification of subaerial sediment-water flows. In: Costa JE, Wieczorek GF (eds) Debris flows/avalanches—process, recognition, and mitigation: Rev Eng Geology 7:1–12

Pierson TC, Scott KM (1985) Downstream dilution of a lahar: transition from debris flow to hyperconcentrated streamflow. Water Res Res 21:1511–1524

Punongbayan RS, Ruelo HB (1985) Profile morphology and internal structure of Mayon Volcano. Philippine J Volcanol 2 (1 & 2)

Qian Y, Wenhai Y, Wenlin Z, Xiuwen C, Longrong Z, Wengui X (1980) Basic characteristics of flow with hyperconcentration of sediment. In: Boning L (ed) Proc Int Symp River Sedimentation. Beijing, Guanghua, pp 175–184

Rabonza G (2006) Philippines: NDCC media update-Typhoon Reming (Durian). Technical Report. Office of Civil Defense

Ramos-Villarta S, Corpuz E, Newhall C (1985) Eruptive history of Mayon volcano, Philippines. Philippine J Volcanol 2:1–35

Rodolfo K (1989) Origin and early evolution of lahar channel at Mabinit, Mayon Volcano, Philippines. Geol Soc Amer Bull 101:414–426

Rodolfo K, Arguden A (1991) Rain-lahar generation and sediment-delivery systems at Mayon Volcano, Philippines. In: Fisher R, Smith G (eds) Sedimentation in volcanic settings. Soc Econ Paleontol Mineral Spec Pub 45, pp 71–87

Rodolfo K, Umbal J, Alonso R, Remotigue C, Melosantos M, Salvador J, Evangelista D, Miller Y (1996) Two years of lahars on the western flank of Mount Pinatubo: initiation, flow processes, deposits, and attendant geomorphic and hydraulic changes. In: Newhall C, Punongbayan R (eds) Fire and mud: eruptions and lahars of Mount Pinatubo, pp 989–1013. Philippine Inst Volcanol Seismol, Quezon City, pp 989–1013

Segerstrom K (1950) Erosion studies at Paricutin volcano, State of Michoacan, Mexico: US Geol Surv Bull 956-A:164

Smith GA, Lowe DR (1991) Lahars: Volcano-hydrologic events and deposition in the debris flow—hyperconcentrated flow continuum. In: Fisher RV, Smith G (eds) Sedimentation in Volcanic Settings. Soc Econ Paleontol Mineral Spec Pub 45, pp 59–70

Sutikno H, Sakatani (1993) Present conditions of mudflow forecasting and warning system in the area of Merapi, Central Java. First Seminar on Sabo Engineering, Sabo Technical Center, Yogyakarta, 17–20 February 1993, pp 1–17

Suwa H, Sumaryono A (1995) Sediment transportation by storm runoff at the Bebeng river on Mount Merapi. Proceedings of Workshop on erosion control through volcanic hydrological approach (WECVHA), Sabo Technical Center, Yogyakarta, 10–11 January 1995, pp 106–107

Task Group for the International Decade of Natural Disaster Reduction (1990) Report. Bull Volc Soc Japan Ser 2: 35: pp 80–95

Tungol N, Regalado M (1996) Rainfall, acoustic flow monitor records, and observed lahars of the Sacobia River in 1992. In: Newhall C, Punongbayan R (eds) Fire and mud: eruptions and lahars of Mount Pinatubo. University of Washington Press, Seattle, pp 1045–1052

Umbal JV (1986) Mayon lahars during and after the 1984 eruption. Philippine J Volcanol 3:38–59

Umbal JV, Rodolfo KS (1996) The 1991 lahars of southwestern Mount Pinatubo. Philippines and the evolution of a lahar-dammed lake: pp 951–970. In: Newhall C, Punongbayan R (eds) Fire and mud: eruptions and lahars of Mount Pinatubo. Philippine Inst of Volcanol Seismol, Quezon City, pp 1045–1052

Van Westen CJ, Daag AS (2005) Analyzing the relationship between rainfall characteristics and lahar activity at Mount Pinatubo, Philippines. Earth Surf Process Landf 30:1663–1674

Waldron HW (1967) Debris flow and erosion control problems caused by the ash eruptions of the Irazu volcano, Costa Rica. US Geol Surv Bull 1241-I:37

White JDL (1991) The depositional record of small, monogenetic volcanoes within terrestrial basins. In: Fisher RV, Smith G (eds) Sedimentation in volcanic settings. Soc Econ Paleontol Mineral, Spec Pub 45: pp 155–171