Fallout Tephra of the 2006–2007 Eruptions of the Bulusan Volcano, Southern Luzon, Philippines

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Abstract

The Bulusan volcano is one of the active volcanoes in the Philippines, and is located in southern Luzon. In 2006 and 2007, 19 and 7 distinct phreatic eruptions of the volcano occurred, respectively. Each discrete event produced tephra that was dispersed by prevailing winds mainly to the west or southwest of the summit vent, blanketing portions of the western Sorsogon Peninsula. Some events were recorded as explosion-type earthquakes. Whenever possible, fallout tephra deposits were mapped and sampled to determine the volume and composition of material produced from each eruptive event. Based on the dispersal maps, the average volume was estimated to be 10^5 m^3 . No juvenile magma were detected in ash and lithic samples by petrographic and X-ray fluorescence analysis. Therefore, all analyzed samples were considered products of phreatic eruptions.

Key words : Bulusan volcano, phreatic eruption, ash fall, juvenile magma, Philippines

I. Introduction

Bulusan volcano ($12^\circ 46.2' \text{N}$, $124^\circ 03.0' \text{E}$) is situated in the central part of the Sorsogon Peninsula, at the southern end of the Bicol Volcanic Arc (Fig. 1). It is located 70 km southeast of the better known Mayon volcano, and 250 km southeast of metro Manila. It has erupted at least 17 times since its first recorded eruption in 1852. The eruption styles have been classified into two types: (1) Strombolian (e.g., 1918–1919), and (2) phreatic or phreatomagmatic (e.g., 1918–1922, 1979–81, 1983, 1988, 1994–95, 2006–07, 2010–11). Saderra Maso (1911) described the

eruptions of 1852, 1889, and 1894 as having a few small outbursts with the ejection of ash. This is typical of the activity exhibited during the more recent eruptions. Here we describe the eruptive events of 2006 and 2007, and characterize their fallout tephra. Relevant seismic and other related observation data derived from the “Volcano Bulletins” and various “internal reports” of investigations conducted by Philippine Institute of Volcanology and Seismology (PHIVOLCS) are also presented in this paper.

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Fig. 1 Index maps. (A) Active volcanoes in the Philippines (PHIVOLCS, 2002¹⁾). Rectangle indicates area of (B). Numbers for active volcanoes were provided by PHIVOLCS¹⁾. The Bulusan volcano is number “12”. (B) Topographic map around Bulusan volcano. Names of municipalities are also shown. Base map was created from SRTM data using KASHMIR rendering software.

II. Geological setting and history of the Bulusan volcano

The Bulusan volcano is an andesitic strato-volcano and dome complex on the northeast rim of the 41-cal kBP Irosin caldera, and is one of the most active volcanoes in the Philippines (PHIVOLCS, 2002¹⁾). It stands 1559 m above sea level with a base area of approximately 400 km². The volcano has rugged topography resulting from multiple lateral vent and dome growth, forming vertical cliffs, deep gullies, and gorges primarily composed of lava flow deposits, and is flanked by small, gently sloping pyroclastic and lahar aprons. Grass and bare ash, thick dense tropical forest, and coconut groves cover the upper, middle, and lower slopes, respectively. The 2006–2007 eruptive

events and the more recent November 2010 and February 2011 events (e.g., Okuno *et al.*, 2011; Kinoshita and Laguerta, 2014) bring the number of historical Bulusan eruptions to 17. PHIVOLCS has instituted an alert level system (Table 1) to evaluate the activity of the volcano.

III. Chronology of the eruptive events

Dispersal maps of the ash falls of the 2006 and 2007 eruptions at Bulusan volcano are shown in Figs. 2 and 3. In this chapter, we describe the eruptions in chronological order, including seismic and other related observation data.

1) The 2006 eruptive events and fallout tephra

Nineteen distinct phreatic eruptive events occurred at Bulusan in 2006. Prior to the first event

Table 1 Alert level signals for the Bulusan volcano.

Alert Level	Criteria	Interpretation
0	Background, quiet	No eruption in foreseeable future
1	Low level of seismic, fumarolic, and other unrest	Magmatic, tectonic or hydrothermal disturbance; no eruption imminent
2	Moderate level of seismic, other unrest with positive evidence for involvement of magma	Probable magma intrusion; could eventually lead to an eruption
3	Relatively high and increasing unrest, including numerous low frequency volcanic earthquakes, accelerating ground deformation, increasing fumarolic activity.	Increasing likelihood of an eruption, possibly explosive, probably within days to weeks.
4	Intense unrest, including harmonic tremor and / or many "long-period" (i.e., low frequency) earthquakes and / or dome growth and / or small explosions	Magma close to or at the earth's surface. Hazardous explosive eruption likely, possibly within hours or days.
5	Hazardous eruption in progress. Hazards in valleys and downwind.	

on March 21, its seismic network recorded 73 high-frequency volcanic earthquakes in the 24-h period between 0600 h Philippine Standard Time (PST) on March 18 and 0600 h PST on March 19 (Table 2). The seismic swarm marked in an increase in the average daily volcanic seismicity compared to the typical background rate of less than five events daily. As a precaution against the sudden hydrovolcanic eruptions for which Bulusan is known, PHIVOLCS on March 19 raised the volcano status from Alert Level Zero (no alert) to Alert Level 1 to reflect the elevated seismicity. The first of the phreatic explosions occurred at 2258 h PST on March 21, producing an ash column that rose 1.5 km above the summit. The Bulusan Seismic Network detected an explosion-type earthquake that lasted for 20 min, and lightning flashes and rumbling sounds accompanied ash ejection. Three subsequent explosion-type earthquakes were also detected at 2330 h, 2332 h, and 2337 h PST, but the corresponding eruptive events could not be observed due to the obscuring of the summit. One hour after these events, light ash fall (approximately 5 mm in thickness) was reported by residents on the northern, western, and southwestern flanks of the volcano, including the barangays (villages) of Cogon, Tinampo, Gulang-gulang, and Bolos in Irosin, and Puting Sapa and Bura-Buran in the Juban Municipalities

(Fig. 1B). After this series of events, the number of volcanic earthquakes decreased significantly until the succeeding eruptive events on April 29. Lower-magnitude phreatic eruptions in 2006 are listed and described in Table 2.

Another series of phreatic eruptions occurred in June 2006, after which a Quick Response Teams (QRT) was deployed by PHIVOLCS to map and sample all recently emplaced deposits (Arpa *et al.*, 2006). The June events were relatively low magnitude, with ash plumes rising 1–2 km from the summit of the volcano. Minor pyroclastic flows may have been generated, but these were likely confined to the deep gullies near the summit area, within the 4-km-radius Permanent Danger Zone (PDZ). In general, however, the products of all of the March to June 2006 eruptions were largely characterized by fallout tephra. Dispersal maps for the discrete events are shown in Fig. 2. Rough calculations of the cumulative volume of tephra deposits from the March 21, April 29, May 25 and 31, and June 7, 10, 13 and 18 events yielded values of approximately $1 \times 10^6 \text{ m}^3$. Bulusan lapsed into a period of quiescence for more than 5 weeks following the June events, as seismic, visual, and ground-deformation monitoring parameters were recorded at baseline levels. On July 29, 2006 PHIVOLCS lowered the volcano status to Alert Level 1. Then, without any seismic precursors,

Fig. 2 Dispersal maps of ash fall from the phreatic eruptions at Bulusan volcano from March to June 2006 (modified from Arpa *et al.*, 2006). (A) March 21, 2006, (B) April 29, 2006, (C) May 25, 2006, (D) May 31, 2006, (E) June 7, 2006, (F) June 10, 2006, (G) June 13, 2006, (H) June 18, 2006.

Fig. 3 Dispersal maps of ash fall from the phreatic eruptions at Bulusan volcano in 2007 (modified from PHIVOLCS Bulletins and QRT results). (A) Broken line showing the distribution of April 8, 2007 ash fall. (B) Broken line showing the distribution of July 31, 2007 ash fall.

phreatic activity resumed as an explosive event on October 10, propelling an ash column 3 km above the summit vent. A series of eruptive events followed on October 19, 23, 25, 30, and December 20, 2006 (Table 2).

2) The 2007 eruptive events and fallout tephra

Phreatic eruptions recurred on January 24 and 26, 2007 accompanied by explosion-type earthquakes and fallout tephra (Table 3). Volcanic activity waned until a new swarm of high-frequency volcanic earthquakes began on April 5, preceding a series of eruptive events. The first of these was the April 8 explosion, which produced an ash column 4 km above the summit vent, and showered the western sector of the volcano with thin ash fall. After this event, a new fissure was observed in the northern portion of the volcano summit. Another eruptive event occurred on April 9, but it was obscured. A QRT was again dispatched on April 12–17, 2007 to document the resumption of activity. Mapping and sampling of *in situ* April deposits was not possible because rain had washed away the associated fallout tephra. However, the extents of the deposit could be constrained in the field, and deposit thicknesses in localities were reasonably documented through remnant deposits

and resident interviews (Bornas *et al.*, 2007a, b, c). It was through interviews that local vernacular words for the particle sizes of fallout tephra resurfaced, a feature unique to communities surrounding Bulusan. Although residents called fine ash “*abo*” similar to most Pilipino dialects, they had special names for medium- to coarse-sand-grained ash, “*baybay*” and lapilli, “*batiris*” that were aptly used to describe the April fallout (Table 4). Figure 3A shows the extent of the terrestrial fallout area, approximately 260 km². Assuming an average thickness of 1 mm, the total terrestrial fallout volume was conservatively estimated at $2\text{--}3 \times 10^5 \text{ m}^3$.

At 0937h PST on July 31, 2007, Bulusan erupted for the last time that year, propelling a 5-km-high eruption column visible in neighboring Albay Province (Tables 3 and 5). The top of the eruption column was observed as being sheared off by tropospheric winds, and remained suspended for approximately 1.5 h prior to complete fallout (Bornas *et al.*, 2007d). Another QRT was dispatched for mapping of the fallout tephra, sampling, and an aerial survey onboard Philippine Air Force helicopters. Figure 3B shows the areal extent of the terrestrial fallout area, which covered roughly 220 km². Assuming an average thickness of

Table 2 Chronology of the Bulusan volcano eruptions in 2006 (compiled from PHIVOLCS Volcano Bulletins).

Date	Time (PST)	Eruptive activity and related phenomena	Seismic data	Dispersal / Areas affected
19 Mar.	0600	Raised Alert Level from 0 to 1	73 high-frequency-type imperceptible volcanic earthquakes; swarm lasted until 21 Mar.	
21 Mar.	2258-2318	Phreatic eruption with lightning flashes and rumbling sounds; 1.5 km column; drifted N, W, and SW	Explosion-type earthquake	Municipality of Irosin- <i>Barangays Cogan, Tinampo, Gulang-gulang and Bolos (light ash fall)</i> ; Municipality of Juban- <i>Barangays Puling Sapa and Bura-Buran (light ash fall)</i>
21 Mar.	2330, 2332 and 2337	Phreatic eruption; no visual siting because summit obscured	Explosion-type earthquakes	
08 Apr.	2000	Lahar reported along Cogan spillway; debris flow with small logs		Channel confined; lahar deposited 3 km downstream at Gulang-Gulang Bridge; road to Mt. Jormajan impassable
09 Apr.	1036-1058	Lahar reported along Cogon spillway;		Channel confined; lahar signal detected by Jorma-an seismic station
29 Apr.	1044-1144	Phreatic eruption with faint rumbling sounds heard along western sector of Bulusan; drifted WSW and NW; light gray ash column that rose to about 1.5 km above the summit; drifted WSW and NW	3 explosion-type earthquakes	Municipality of Juban- <i>Light ash fall in Barangays Sangkayon, Bura-Buran and Anio</i> Municipality of Irosin- <i>Barangay Cogan</i>
25 May	2117-2130	Phreatic eruption; summit obscured	Explosion-type earthquake	Municipality of Juban- <i>Barangays Bacolod, Sangkayon, Puling Sapa, Rangas, Mapili, Caladgao and Bura-Buran</i> Municipality of Irosin-, <i>Barangay Bolos</i>
31 May	1617-1632	Phreatic eruption drifted W and WNW; light gray ash column that rose to about 1.5 km above summit	Explosion-type earthquake	Ash deposits ranged from trace to 2 mm thick; affected Municipality of Juban- <i>Barangays Bacofod, Sangkayon, Puling Sapa, Caladgao and Bura-Buran</i> Municipality of Irosin- <i>Barangays Bolos and Cogon</i>
07 Jun.	2017-2030	Phreatic eruption with ash column that rose to about 2.0 km above summit; drifted SW, N and W; raised Alert Level from 1 to 2	Explosion-type earthquake; another smatter E-type earthquake at 0226 of 08 Jun.	Municipality of Juban- <i>Barangays Sangkayon, Aroroy (trace) and Juban Proper (1 mm thick)</i> Municipality of Irosin- <i>Barangays Bolos and Gulang-gulang</i> Municipality of Casiguran- <i>Casiguran Proper (0.5-2 mm), Infagadian (light ash fall), San Juan and Ponong (2 mm), San Antonio (1 mm)</i>
10 Jun.	1218-1243	Phreatic eruption with ash column that rose to 1.0 km above summit; drifted NE and E	Explosion-type earthquake with rumbling sound and lightning flashes	Municipality of Bulusan- <i>Barangays San Isidro, Sta. Barbara, Buang and Purog</i> Municipality of Casiguran- <i>Barangays Inlagadian & Escuafa</i>

Table 2 (continue)

Date	Time (PST)	Eruptive activity and related phenomena	Seismic data	Dispersal / Areas affected
13 Jun.	1904-1917	Phreatic eruption with ash column that rose to about 1.5 km above summit; drifted NW	Explosion-type earthquake with rumbling sounds and lightning flashes	Municipality of Juban- <i>Barangays Aroroy, Mabini and Aniog</i> (<i>heavy ash fall at least 7 mm</i>), <i>Bacolod and south of Juban Poblacion</i> (<i>light ash fall 1 mm</i>) Municipality of Casiguran- <i>San Juan</i> (<i>trace</i>)
18 Jun.	1556	Phreatic eruption with ash column that rose to ca. 1.5 km above summit; drifted W	Explosion-type earthquake	Municipality of Irosin- <i>Barangays Bolos, Sangkayon</i> (<i>5 mm</i>) and <i>Puling Sapa</i>
20 Jun.	2013	Phreatic eruption; summit obscured; lahar occurrence	Explosion-type earthquake; lahars generated with lahar signals recorded for 17 min.	Coincided with heavy rains
24 Jun.	2300	Lahar occurrence Cogan spillway with ave. Thickness of deposits ca. 3 m	No Lahar signals recorded	Channel confined; debris flow with boulder-sized rocks at upper reach; hyperconcentrated streamflow at lower reach of the channel
28 Jun.	0206-0210	Phreatic eruption; summit obscured	Explosion-type earthquake	
29 Jun.		Lowering of Alert Level from 2 to 1		
10 Oct.	1716-1725	Phreatic eruption with ash column that rose to ca. 3 km above summit; drifted SW-SSE	Explosion-type earthquake accompanied by rumbling sound heard as far as 6 km from the summit	Municipality of Irosin- <i>Barangays San Benon, Sto. Domingo and Patag</i> (<i>5-1.5 mm thick</i>) Municipality of Bulusan- <i>Barangays San Roque, San Rafael, San Francisco, Dangkalan and Bulusan Proper</i>
19 Oct.	1844-1846	Phreatic eruption with no description of ash column	Explosion-type earthquake	Light ash fall experienced at Barangays Tinampo and Cogan in Irosin
23 Oct.	0630	Phreatic eruption with 1.0 km ash column; drifted SW and SE	Explosion-type earthquake accompanied by rumbling sounds	Municipality of Irosin- <i>Barangays Monbon and Tinampo</i> (<i>0.5 mm thick</i>), <i>Gulang-gulang</i> (<i>trace</i>)
25 Oct.	0930	Minor lahar occurrence and mud stream flow		Channel-confined in Barangay Cogan, Gulana-aulana in Irosin
30 Oct.	1156-1227	Phreatic eruption with 1.0 km ash column; drifted N and NW	3 explosion-type earthquake accompanied by rumbling sounds	Municipality of Casiguran- <i>Barangays Inlagadian, San Juan, Casay and Escuafa</i> (<i>trace to 1.0 mm</i>) Municipality of Gubat- <i>Barangays Bentuco, Tugawe, Benguet, Rizal, Buenavista, Ariman, Tabi, Bulacan, Panoaniban, Carriedo and Gubat Prover</i>
20 Dec.	0109-0129	Phreatic eruption with 1.0 km ash column; drifted N and NW	Explosion-type earthquake accompanied by rumbling sounds and lightning flashes	Municipality of Irosin- <i>Barangays Casini</i> (<i>4 mm</i>), <i>Tulay</i> (<i>3 mm</i>), <i>Salvacion</i> (<i>2.5 mm</i>) <i>Monbon and Buenavista</i> (<i>1.5 mm</i>), <i>Liyang</i> (<i>1 mm</i>), and <i>Poblacion</i> (<i>0.5 mm</i>) Municipality of Bulan- <i>Trece and Gate</i> (<i>trace</i>)

Table 3 Chronology of the Bulusan volcano eruptions in 2007 (compiled from PHIVOLCS Bulletins).

Date	Time (PST)	Eruptive activity and related phenomena	Seismic data	Dispersal / Areas affected
24 Jan.	2206-2216	Phreatic eruption	Explosion-type earthquake	Municipality of Irosin- <i>Barangays Cogan, Monbon, San Benon, Gulang-gulang and Tinampo (trace)</i>
25 Jan.	2228-2224	Phreatic eruption with 1.0 km ash column; drifted SW	Explosion-type earthquake	Municipality of Irosin- <i>Barangay Monbon</i>
07 Apr.	48 hr observation	Seismic swarm, advisory issued	68 high frequency-type imperceptible volcanic earthquakes	
08 Apr.	1745-1812	Phreatic eruption with 4.0 km ash column; drifted SW; small lahars and muddy streamflows along proximal reach of the channels on southwest flank	Explosion-type earthquake	Municipality of Irosin- <i>Barangays Cogan, Monbon, Tinampo, Gulang-gulang, Bolos, Omagon and Sangkayon (1.5-1mm)</i> Municipality of Juban- <i>Barangays Bura-buran and Bacolod (1.5-1mm)</i> Municipality of Magallanes- <i>Barangay Siuton</i> Municipality of Bulan- <i>Barangays Cadandanan, Busay, Palale, San Francisco and Sumagongsong</i>
09 Apr.	0611-0631	Phreatic eruption; not observed due to thick rain clouds that covered the volcano's upper slopes Another phreatic eruption	Explosion-type earthquake accompanied by rumbling sounds	
	0716-0736			
9-11 May	72 hr observation	Seismic swarm	42, 65 and 97 high-frequency-type imperceptible volcanic earthquakes, respectively	
12 May	1030-1105	Phreatic eruption with 4.0 km ash column; drifted WSW and WNW	Explosion-type earthquake with rumbling sound	Municipality of Irosin- <i>Barangays Cogan, Monbon, Tinampo and Gulang-gulang</i> Municipality of Juban- <i>Barangays Snagkayon, Bura-buran and Bacolod</i> Municipality of Magallanes- <i>Barangay Siuton</i> Municipality of Bulan- <i>Barangays Cadandanan, Busay, Palale, San Francisco and Sumagongsong</i>
12 to 19 May	0800-0800	Seismic swarm	83, 7, 51, 93, 92, 78 and 187 high-frequency type imperceptible volcanic earthquakes, respectively	
20 May	24 hr observation	Seismic swarm; raising of Alert Level from 1 to 2	223 high-frequency-type imperceptible volcanic earthquakes	
13 Jul.		Lowered Alert Level from 2 to 1	Since 20 May 2006 ash ejection, all monitored key parameters including seismic showed a decline in activity	

Table 3 (continue)

Date	Time (PST)	Eruptive activity and related phenomena	Seismic data	Dispersal / Areas affected
31 Jul.	0937-0957	Phreatic eruption with 5.0 km ash column; drifted WSW and WNW	No significant increase in seismic activity prior to ash ejection; explosion-type earthquake with rumbling sound	Municipality of Irosin-Barangays <i>Bolos and Caladgao</i> (2.5 mm), <i>Omagom</i> (1.5 mm), <i>Cogan, Gulang-gulang and Gabao</i> (1 mm), Municipality of Juban-Barangays <i>Puling Sapa and Sangkayon</i> (3 mm), <i>Bura-buran</i> (2 mm) and <i>Bacolod</i> (0.5 mm)
04 Oct.	0134 and 0139	Phreatic eruption not visually observed; slight inflation at the NE flank of the volcano (03 Oct. reading)	No significant increase in seismic activity since the 31 Jul. eruption except during the past 24 hr with 40 high-frequency-type imperceptible volcanic earthquakes; explosion-type earthquake	Municipality of Bulusan-Barangays <i>Upper San Jose</i> (1 mm), <i>Lower San Jose</i> (0.5 mm), <i>San Roque, San Rafael, Sitio Tawog of Porog, Porog Proper and Bulusan Proper</i> (light ash fall to trace)
15-16 Oct.		Lahar occurrences	Coincided with recorded high frequency signals at Upper Inlagadian seismograph	SE area (Mapaso)-debris flow with boulders and sand SW area (Monbon, Cogon, Gulang-gulang) -debris flow with small logs, boulders and sand NW area (Ranga, Anog)-muddy streamflow boulders; channel confined

1 mm, the total terrestrial fallout volume was estimated at $2 \times 10^5 \text{ m}^3$.

IV. Petrological and grain size characteristics of the 2006-2007 Bulusan ash falls

1) Experimental procedure

Fallout tephra samples were collected from almost all Bulusan eruptive events in 2006 and 2007 (Table 6). The samples were analyzed for possible inputs from juvenile magma, as a method of detecting precursors of a potentially larger magmatic eruption. Mineral and lithic compositions of the ash were identified under a petrographic microscope. Thin sections were prepared by smearing ash samples on a slide then polishing to an ideal thickness. Bulk ash and lithic fragments were further analyzed for geochemical composition using a Shimadzu 1800 X-ray fluorescence (XRF) spectrometer at PHIVOLCS. Samples were fused into glass beads with proportions of 0.7000 g $\pm$ 0.0005 g of sample and 7.000 g $\pm$ 0.0005 g of flux ($\text{Li}_2\text{B}_4\text{O}_7$ - LiBO_2). Major element concentrations were determined by quantitative analysis using calibration lines from established

standards (JB-3, JB-1a, JA-2, JG-3, JA-1, JG-1a). Two standards were analyzed as unknowns to test for accuracy. Grain size analysis was performed with a wet sieve, using 20 g of limited samples and 150 g of more-abundant samples, to identify ash samples suitable for XRF analysis.

2) Sample descriptions

Table 5 shows the basic petrologic descriptions of selected fallout tephra samples. The majority of the samples were composed of gray, fine- to medium-sand ash. One sample (BV070731-Sangk) contained coarser grains with some lapilli-sized clasts. In thin section, the ash samples were composed of minerals, lithics, and brown glass fragments that were sometimes devitrified (e.g., BV-070512). Identified mineral components included plagioclase, pyroxene, amphibole, and biotite. Glass shards were neither cusped nor platy, indicating that fresh magma may not have been involved in the phreatic events.

Analysis of major element compositions by XRF was performed on selected bulk ash samples. Samples BV070512-Juban and BV070512-Bulan were collected from different localities from the

Table 4 Fallout tephra survey for the April 8, 2007 eruption of the Bulusan volcano (after Bornas *et al.*, 2007a-d).

Latitude	Longitude	Barangay / Site	Municipality	Ash fall	Date	Time (PST)	Ash fall Description	Additional Information
12.7501	124.0129	Cogan	Irosin	ca. 2 mm	09 Apr.	0500	Fine and sandy ash	Lahar shortly after ash fall; Ash fall following eruption rumbling sound with lightning
				Trace	12 Apr.			
				None	08 Apr.			
12.7495	124.0112	Cogan Elementary School	Irosin	1.5 mm				Ash sample (remnant)
12.738	124.0098	Tinampo Elementary School	Irosin	Trace				Ash sample (disturbed)
12.7404	123.9987	Gulang-gulang	Irosin	ca. 1 mm	08 Apr.	0700-0800	Fine ash	Eruption with rumbling sound; AF with lightning and followed by rainfall
12.7360	123.9864	Gabao High School	Irosin	None				Rumbling sound ca. 0630 AM.
12.7513	123.9730	Guruyan Elementary School	Irosin	4-5 mm	08 Apr.	0530	Fine and sandy ash	Ash sample
12.6626	123.9335	N. Roque Elementary School	Bulan	None				
12.6677	123.8788	Zone 8	Bulan	None				
12.6803	123.8756	Imelda	Bulan	Trace	08 Apr.	0600	Fine ash	
12.6940	123.8857	Somagongsong	Bulan	Trace	08 Apr.	0700-0800	Fine ash lasting until 1100	
12.7184	123.9036	San Francisco	Bulan	> Trace	08 Apr.	0600	Fine and sandy ash, lasting before noon	Rain fall in PM
12.7385	123.9007	E. Quirino	Bulan	2 mm	08 Apr.	0600	Sandy ash lasting until noon, smelly	Sound like loud thunder heard before ash fall; rain fall next day
12.7558	123.9067	Cadandanan	Bulan	Trace	08 Apr.	0700	Fine ash, lasting 30 mins, sulfur smell	Rain fall the next day
12.7773	123.9025	Tula-tula Sur	Magallanes	Trace	08 Apr.	0800	Fine ash lasting 20 mins	With simultaneous rain fall
12.7894	123.8828	Siuton	Magallanes	Trace	08 Apr.	0700	Fine ash	Ensuing rainfall
12.7963	123.8654	Siuton	Magallanes	Trace	08 Apr.	0800	Fine ash, intermittent for 2 hrs	Ensuing drizzle
12.8056	123.8498	Caditaan	Magallanes	Trace	08 Apr.	0700	Fine ash, intermittent all day (?)	
12.8196	123.8389	Aguada Sur	Magallanes	Trace	08 Apr.	0800	Intermittent ash	Rainfall in the PM
12.8203	123.9724	Lahong	Magallanes	None				
12.6914	124.0110	Salvacion	Irosin	None				
12.7009	123.9987	Satang	Irosin	None				
12.7066	123.9933	Gumapao	Irosin	None				
12.7215	123.9848	Tong dol	Irosin	Trace	08 Apr.	0700	Fine ash, lasting 2 hrs	Drizzle the next AM
12.7239	123.9780	Tong dol	Irosin	> Trace	08 Apr.	0600	Fine ash, lasting 1 hr	
12.7759	124.0037	Putting Sapa	Juban	1 mm	08 Apr.	0600	Fine and sandy ash, lasting 1 hr	Rain fall the next AM; ash sample
12.7767	123.9891	Sangkayon Elem School	Juban	2 mm			Fine and sandy ash	Ash sample (disturbed)

Table 5 Fallout tephra survey for the July 31, 2007 eruption of the Bulusan volcano (after Bornas *et al.*, 2007a-d).

Locality	Latitude	Longitude	Grainsize	Thickness	Description	Respondents / Remarks	Time / Duration
Puling Sapa, Juban	12.7759	124.0035	Lapilli (max 2 cm) with minor fine ash	1 to 2 mm	Grains mainly angular unvesiculated andesite, minor hydrothermally altered lithics		5 min. after eruption onset / 30 min.
Sangkayon Elementary School, Juban	12.7768	123.9893	Lapilli with minor fine ash	3 mm	Similar to Puling Sapa, few larger lapilli		
Bolos, Juban	12.7510	123.9842	Coarse with minor fine ash				
Cogan, Irosin						BRGY. CAPT.: "Batiris" could be heard hitting rooftops; estimates column height at 5 km	5 mins after eruption onset / 30 min.
Lahong, Juban	12.8202	123.9721	No ash fall			BELEN CELINO: Audible sounds described as "dalugdog", "hagubuhub", "parang sinapna"	
Lahong, Juban	12.8228	123.9596	Trace			JUDITH MERCADERO: Audible sounds described as "hugalbung"; smell of sulfur	
Caditaan, Magallanes	12.8096	123.8495				MON MORTEGA: coarse ash ("baybay") with fine ash; smell of sulfur	1000 / 30 min.
Ibalon, Siuton, Magallanes	12.7967	123.8587	Coarse with minor fine ash		Remnant deposits on leaves	Passerby	1000 / 30 min.
Siuton, Magallanes	12.7960	123.8730	Coarse ash				
Siuton, Magallanes	12.7938	123.8756		2 to 3 mm	Road thickness measurement		
Busay, Magallanes	12.7822	123.9018		> ca. 2 mm		ALMA SIMON: "baybay" falling loudly ("lagatak") on leaves, painful to the skin; smell of sulfur	
Cadandanan, Magallanes	12.7595	123.9051				MARLENE OPENA: gray "baybay"	0900-1200
Palale, Bulan	12.7428	123.9039				MADING DELFO: Coarse ash ("baybay"); rain fall ca. 1300	1200
San Francisco, Bulan	12.7095	123.8970				RUFINO GORDOLA: Fine ash reaching the sea; rain fall at 1500	1000 / until 1130
Somagongsong, Bulan	12.6932	123.8851		Trace		PURISIMA DIPAYA: "papatak lpatak"	
Detachment 509, Bulan	12.6776	123.8736		Trace		MERCED AMILANO: fine ash; "tinik-tinik" 30 min. after	1200
Gabao, Irosin	12.7310	123.9804				GEMMA HICAB: fine ash; kicked up by vehicles; drizzle (tinik-tinik) at 1300	1000 / until 1300
Guruyan Elementary School Guruyan, Irosin	12.7513	123.8897	Coarse with minor fine ash	ca. 1 mm	Disturbed sample	LOUIE CALBAYO: fine with coarse ash; smell of sulfur; "tinik-tinik" at 1300; audible sound described as "dumagundong"	1100 / < 1 hr
Basketball court at Sankayon, Juban	12.7736	123.9856	Lapilli	2 to 3 mm	Disturbed sample	VIRGILIO GRIEGO: earliest fallout were cigarette-diameter grains followed by "baybay"	15 mins after emption onset / 30 mins

Table 6 Major element composition of the Bulusan ash from the May 25, 2006 and May 12, 2007 eruptions, and composition of the lithic fragments (LAP) from the July 31, 2007 eruption.

Sample	BV060525	BV070512- Juban	BV070512- Bulan	BV070731- LAP1	BV070731- LAP2	BV070731- LAP3	BV070731- LAP4	BV070731- LAP5
SiO ₂	61.58	61.17	61.01	55.08	63.60	59.17	56.49	62.46
TiO ₂	0.56	0.56	0.56	0.65	0.56	0.51	0.63	0.57
Al ₂ O ₃	17.56	17.69	17.78	15.12	18.97	18.23	17.96	17.92
Fe ₂ O ₃	6.75	6.69	6.62	8.21	6.41	6.26	7.68	11.35
MnO	0.07	0.09	0.10	0.17	0.05	0.12	0.16	0.01
MgO	1.83	2.03	2.11	4.49	1.94	3.08	4.13	0.81
CaO	6.48	6.66	6.79	11.88	5.05	7.47	8.21	4.22
Na ₂ O	2.53	3.07	3.11	2.77	2.35	3.30	2.97	1.57
K ₂ O	1.59	1.81	1.72	1.44	0.91	1.69	1.54	0.95
P ₂ O ₅	1.05	0.21	0.20	0.19	0.17	0.16	0.23	0.14
Total	91.08	91.7	92.48	94.66	93.65	97.69	97.32	95.98

same eruption event. Lithic fragments were selected from different lithic groups based on hand specimen characteristics. Bulk ash analysis is typically not ideal because: (1) the components of ash originate from different sources (e.g., deposits of different eruptions); and (2) significant aerodynamic fractionation occurs during ash transport and deposition. Tests of selected samples, such as that of the July 31, 2007 eruption (Fig. 4), demonstrated that XRF analysis of different component sizes from a single sample yielded wide variation in composition. This shows that the analysis of bulk ash is not valid if the sample contains a high grain-size fractionation. However, fallout tephra samples that are characterized by a dominant particle size range can yield good major element compositions. For example, ash samples from the May 12, 2007 eruption yielded acceptable results from bulk ash analysis (Fig. 5). Specifically, acceptable samples include those collected 9 km west (BV070512-Juban) and 17 km southwest (BV070512-Bulan) of the crater. Both samples were composed of mostly 3 ϕ to finer grains, specifically 80 wt.% and 85.5 wt.%, respectively. These samples demonstrated that bulk ash analysis could be applicable if fallout tephra is dominantly fine- to medium-grained,

Fig. 4 Grain size distribution for ash samples from the July 31, 2007 eruption taken from Sangkayon and Gurayan, which are located 9 and 10 km west of the crater, respectively. High variation in grain size was observed between the two sample sites, despite the short distance between them and their mutual location west of the crater. Chemical analysis of bulk ash was not possible.

shows little grain size fractionation irrespective of distance from the vent, and is assumed to have fragmented from a homogenous source. Major element composition of the May 12 and 25, 2006 ash samples, as well as selected lapilli-sized lithic fragments from the fallout tephra of the July 31, 2007 eruptive event, are detailed in Table 6. Ash samples were andesitic in composition with consistent SiO₂ of 61 wt.%, whereas lithic compositions varied across the basaltic andesitic

Fig. 5 Total alkali ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) versus silica (SiO_2) for bulk ash and lapilli of selected samples. Closed circle, open and closed triangles indicate samples BV060525, BV070512 (-Juban, -Bulan), BV070731 (-LAP1, -LAP2, -LAP3, -LAP4 and -LAP5), respectively. Samples collected from both sites for the May 12, 2007 ash showed a similar composition, within the andesite range. The May 25, 2006 ash plotted in the same area. The individual lapilli of BV070731-Sangk (July 31, 2007) showed greater compositional variation, ranging from basaltic andesite to dacite.

and dacite range. Both the chemistry and mineral components are consistent with those of the post-caldera volcanism, which includes Bulusan (Delfin *et al.*, 1988, 1993; McDermott *et al.*, 2005).

Based on the results of these analyses, samples collected from the 2006–2007 Bulusan eruptions do not appear to be similar to ash erupted from juvenile magma. Although blocky to angular glass grains typical of andesitic ash occur in the samples, very few appeared clear and without alteration. A brown glass shard identified in the May 25, 2006 sample appeared unaltered under the petrographic microscope, but fine veins of alteration clays may be missed with this method. The wide compositional range of the analyzed lapilli from the July 31, 2007 event (Sample BV070731-Sangk) denotes multiple deposit sources (Fig. 5). Some degree of alteration can be further interpreted from the lower K_2O content of the lithic samples with higher SiO_2 content (Table 6). Based on texture and chemistry, it could be reasonably deduced that the lapilli-sized

lithics are non-juvenile in origin. Overall, the studied samples appear to have been produced by fragmentation of pre-existing vent rock in a phreatic eruption.

V. Concluding remarks

The 2006 and 2007 phreatic eruptions primarily generated ash fall tephra with no significant emplacement of pyroclastic flows. All fallout tephra deposits covered the western portion of Sorsogon Peninsula. Based on dispersal maps, the volume of each tephra was approximately 10^5 m^3 . Explosion-type earthquakes accompanied some eruptions. Petrographic and X-ray fluorescence analysis in the laboratory did not detect juvenile magma from any of the tephra samples.

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Notes

- 1) http://volcano.phivolcs.dost.gov.ph/update_VMEPD/Volcano/VolcanoList/bulusan.htm [Cited 2011/1/25/].

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フィリピン・ルソン島南部，ブルサン火山

2006-2007 年噴火による降下火山灰

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ルソン島南部のブルサン火山では、2006 年に 19 回、2007 年に 7 回の水蒸気噴火が発生した。それらの噴火によるテフラは、山頂火口の上空で西または南西方向に吹く卓越風に運ばれ、ソルソゴン半島の西部地域を覆った。いくつかのイベントでは、爆発地震が記録された。降下テフラの分布調査と試料採取ができた場合に、それらの噴出

量の推計と構成物質の検討を行った。それぞれの降下テフラの体積は、得られた分布図から、およそ 10^5 m^3 の規模と推定された。火山灰の岩石記載的観察や蛍光 X 線分析では本質物質は検出されず、すべて水蒸気噴火によるものと結論づけられた。

キーワード：ブルサン火山，水蒸気噴火，降下火山灰，本質物質，フィリピン

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