

Journal of Volcanology and Geothermal Research 100 (2000) 9–50

Journal of volcanology and geothermal research

www.elsevier.nl/locate/jvolgeores

10,000 Years of explosive eruptions of Merapi Volcano, Central Java: archaeological and modern implications

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Abstract

Stratigraphy and radiocarbon dating of pyroclastic deposits at Merapi Volcano, Central Java, reveals \sim 10,000 years of explosive eruptions. Highlights include:

(1) Construction of an Old Merapi stratovolcano to the height of the present cone or slightly higher. Our oldest age for an explosive eruption is 9630 ± 60^{-14} C y B.P.; construction of Old Merapi certainly began earlier.

(2) Collapse(s) of Old Merapi that left a somma rim high on its eastern slope and sent one or more debris avalanche(s) down its southern and western flanks. Impoundment of Kali Progo to form an early Lake Borobudur at \sim 3400 ¹⁴C y B.P. hints at a possible early collapse of Merapi. The latest somma-forming collapse occurred \sim 1900 ¹⁴C y B.P. The current cone, New Merapi, began to grow soon thereafter.

(3) Several large and many small Buddhist and Hindu temples were constructed in Central Java between 732 and \sim 900 A.D. (roughly, 1400–1000 ¹⁴C y B.P.). Explosive Merapi eruptions occurred before, during and after temple construction. Some temples were destroyed and (or) buried soon after their construction, and we suspect that this destruction contributed to an abrupt shift of power and organized society to East Java in 928 A.D. Other temples sites, though, were occupied by "caretakers" for several centuries longer.

(4) A partial collapse of New Merapi occurred $<1130 \pm 50^{-14}$ C y B.P. Eruptions $\sim 700-800^{-14}$ C y B.P. (12–14th century A.D.) deposited ash on the floors of (still-occupied?) Candi Sambisari and Candi Kedulan. We speculate but cannot prove that these eruptions were triggered by (the same?) partial collapse of New Merapi, and that the eruptions, in turn, ended "caretaker" occupation at Candi Sambisari and Candi Kedulan. A new or raised Lake Borobudur also existed during part or all of the 12–14th centuries, probably impounded by deposits from Merapi.

(5) Relatively benign lava-dome extrusion and dome-collapse pyroclastic flows have dominated activity of the 20th century,

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but explosive eruptions much larger than any of this century have occurred many times during Merapi's history, most recently during the 19th century.

Are the relatively small eruptions of the 20th century a new style of open-vent, less hazardous activity that will persist for the foreseeable future? Or, alternatively, are they merely low-level "background" activity that could be interrupted upon relatively short notice by much larger explosive eruptions? The geologic record suggests the latter, which would place several hundred thousand people at risk. We know of no reliable method to forecast when an explosive eruption will interrupt the present interval of low-level activity. This conclusion has important implications for hazard evaluation. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Merapi Volcano; radiocarbon dating; eruptions; archaeology

1. Introduction

van Bemmelen (1949) discussed collapse of an Old Merapi edifice (Figs. 1 and 2) accompanied by a cataclysmic explosive eruption that laid waste to the surrounding countryside. Adopting an idea that was advanced first by Ijzerman (1891) and Scheltema (1912), and embellished by van Hinloopen Labberton (1922), van Bemmelen argued that the collapse and eruption occurred in 1006 A.D. and weakened the Mataram civilization of Central Java, causing it to move from Central to East Java. Subsequent eruptions built a New Merapi that largely filled the collapse crater. Wirakusumah et al. (1980, 1989) produced a geologic map that recognized the same Old and New Merapi, and added a preliminary radiocarbon chronology; Wirakusumah et al. (1986), Bronto and Sayudi (1995), Bronto et al. (1997) and Andreastuti et al. (2000) added important stratigraphic details.

Berthommier (1990), Berthommier et al. (1990, 1992), Camus (1995) and Camus et al. (2000) infer the earliest growth of Merapi began at least 40,000 y B.P., and a Mount St. Helens-like edifice collapse and lateral blast occurred sometime after 7500 y B.P., and possibly as recently as 2200 y B.P., preceded and followed by lava extrusion and scoria-rich column-collapse pyroclastic flows. Berthommier and co-workers infer alternating lava flows, explosion- and dome-collapse pyroclastic flows, and phreato-magmatic eruptions from about 2200 y B.P. to the present, dominated within the past two centuries by lava extrusion and dome-collapse pyroclastic flows.

To test and recalibrate van Bemmelen's hypothesis, and to understand changes in the Mataram civilization and the potential hazards of future eruptions better, we began to study the pyroclastic stratigraphy of Merapi Volcano in 1981. Our traverses focused on stream valleys, roadcuts on interfluves and deposits on and near temples of the 8th and 9th centuries A.D. Although our work has been more fragmented than we would have liked, and much more still needs to be done, we are able to offer a reconnaissance report upon which others might build. Petrologic information about our pyroclastic samples is reported in a companion paper (del Marmol, 1989).

2. Notes on terminology and age dates

(1) The terminology of pyroclastic flows is as complicated as the phenomenon itself. In this paper, we refer to two main types of pyroclastic flows. "Explosion pyroclastic flows" that originate from explosive eruptions, mostly by collapse of vertically-directed explosions. Their deposits are typically rich in scoriaceous breadcrust bombs. Synonyms include: "awan panas letusan" (Suryo, 1978), "nuée ardente d'explosion vulcanienne" (Lacroix, 1904, 1930) and "St. Vincent-type pyroclastic flows" (Escher, 1933; Macdonald, 1972). "Dome-collapse pyroclastic flows" originate by gravitational failure of lava domes. Synonyms of dome-collapse pyroclastic flows include: "awan panas guguran" ("hot cloud of rockfall type"), "nuées ardentes d'avalanche" (Lacroix, 1904, 1930) and "Merapi-type glowing clouds or pyroclastic flows" (Escher, 1933; Macdonald, 1972). The terms "block-and-ash deposits" and "lithic pyroclastic-flow deposits" are descriptive and do not automatically imply dome collapse, but most such deposits at Merapi are in fact of that origin. We avoid the term "Merapi-type pyroclastic flow" because many pyroclastic flows of Merapi are not from dome collapse, but, rather, from explosive eruptions.



Fig. 1. Merapi as seen from the south. Old Merapi and somma rim (far right) and New Merapi cone (center).

Bardintzeff (1984) divided dome-collapse pyroclastic flows into two subtypes: Merapi-type, without fresh glass, and Arenal-type, containing pumiceous glass. Here, we acknowledge variable densities and glass contents of clasts in dome-collapse pyroclastic flows, but consider all dome-collapse pyroclastic flows under the single name, "dome-collapse".

Grandjean (1931) proposed that a third type of pyroclastic flow, the "glowing cloud from a directed blast" ("nuée péléennes d'explosion dirigée" of Lacroix, 1930) occurred at Merapi during 1931, shortly after the devastating events of December 1930. Kemmerling (1932) argued against such flows, while Escher (1933) accepted them as a reasonable possibility. On interfluves, we have seen deposits from which directed blasts could be inferred; however, we conclude they result from "overbank" or "surge" facies of valley-filling pyroclastic flows rather than from true, Mount St. Helens-style directed blasts (see Abdurachman et al., 2000 – this volume).

Some gradation clearly occurs between explosion

and dome-collapse types when explosive eruptions disrupt a lava dome, and some explosions through domes might have slightly directed character. Rather than define subtypes, we prefer to simply recognize variability in the two major types of pyroclastic flows of Merapi.

Mechanical and explosive comminution of fragments within pyroclastic flows of Merapi always produces ash, some of which is elutriated from the flows. Some elutriated ash is transported in ashcloud surges; the rest is transported by winds and emplaced as fall deposit. We avoid the term "coignimbrite" because many of the source flows are not pumiceous, but the processes of elutriation and transport are the same as those described elsewhere in the literature for coignimbrite ash. In this paper, we use the terms "ash-cloud surge" and "elutriated ash fall".

(2) Several Indonesian terms are used as prefixes to describe geographic features: gunung (mountain or hill), kali (stream, river) and candi (temple). Abbreviations are G., K. and C., respectively.



Fig. 2. Geology of Merapi as inferred by van Bemmelen (1949). Elevations in meters.

(3) Ages are expressed in calibrated calendar years where pertinent to archaeological discussions, and in ¹⁴C years elsewhere. Both forms are given in Table 1, together with the most likely and 1σ range of calendar equivalence.

3. Types and distribution of various deposits

3.1. Domes and lava flows

Most domes of Merapi grow at or near the summit (elevation, 2965 m); most lava flows originate from the same vents as the domes but travel 1-6 km downslope. Lava flows dominate the stratigraphy down to about 1000-1200 m elevation; a few lava flows extended to 900 m elevation. A transition from the steep toes of lava flows to a pyroclastic apron creates a distinct break in slope. For more information on lava flows and domes of Merapi, see van Bemmelen (1949), Wirakusumah et al. (1980), Pratomo (1983), Bahar (1984) and del Marmol (1989).

3.2. Pyroclastic flows

Pyroclastic flows and surges originate from the same summit vents as lava flows (or from collapse of lava domes and flows), but deposit their materials only on the middle and lower slopes of Merapi where accumulation of many such deposits has formed a pyroclastic apron around most of the cone. From about 1000 m to about 700 m elevation (typically, 8-9 km from the summit), thick, poorly sorted pyroclastic-flow deposits dominate in valleys whereas tephra-fall and overbank pyroclastic-flow and pyroclastic-surge deposits dominate on interfluves. From 700 m to about 300 m elevation (\sim 20 km from the summit), pyroclastic-flow and -surge deposits are interbedded with lahar and tephra deposits; below 300 m elevation, lahar and banjir (muddy streamflow) deposits are interbedded with thin, discontinuous layers of ash-fall and (probably) pyroclastic-surge deposits. Discovery along the main highway through Sleman that pyroclastic surges (Fig. 4, unit H-9) might have reached even to 200 m elevation-22 km from the summit-has important implications for hazard zonation.

The distribution of dome-collapse pyroclastic flows is directly linked to shifting loci of lava dome- and flow extrusion and to the gross morphology of the crater rim. Occasionally, a dome grows so large that it can collapse over a crater rim into several possible drainages. For example, Merapi's dome had grown so large by November 1994 that part of it collapsed into Kali Boyong on the south–southwest side of Merapi (Abdurachman et al., 2000 – this volume), rather than into the usual 20th century paths, Kali Krasak, Kali Batang and Kali Blongkeng (Fig. 2).

The direction of explosion pyroclastic flows depends critically on microtopography of the summit region onto which material first collapses. Small notches or other low areas of the crater rim concentrate flow in those directions.

All types of pyroclastic flows at Merapi follow narrow, vertical-walled canyons that have been cut into the pyroclastic and alluvial apron. All types are also capable of overflowing their banks onto flat interfluve surfaces where they leave deposits that are typically finer grained and better sorted than their intracanyon facies. Some of these overbank pyroclastic-flow deposits are cross-bedded coarse sand and lapilli with abundant charred twigs and grasses aligned in the downflow direction; others are planar beds, one to several centimeters thick, resembling tephra layers but also having flow-aligned charred twigs and generally consistent paleomagnetic directions of clasts. Some of the related ash-cloud surge deposits are fines-depleted; others are rich in fines and contain only sparse lapilli. Turbulence and sorting may increase as rock fragments are deposited progressively during flow and the density of the flowing mass decreases. Turbulence and sorting may also increase as flows encounter the roughness and water content of vegetation on interfluves. Explosion-type pyroclastic flows are relatively voluminous and have a greater tendency than dome-collapse flows to go overbank and to have wide zones of associated ash-cloud surge.

The distance that a pyroclastic flow travels at Merapi depends on its volume and manner of formation. Large-volume flows travel farther than smallvolume flows, due to momentum and, perhaps, shielding of the interior of flows from heat loss and other boundary effects. Explosion-type pyroclastic flows often reach >8 km from the summit whereas domecollapse flows rarely reach that distance. The greater mobility of the explosion-type flows results in part from their generally larger volume, higher initial gas

Table 1 Listing of ${}^{14}C$ dates on Merapi, in chronological order

Section and unit Lab no. Field no. Age, B.P Calibrated ag ${}^{14}C$ years (1 σ range) c		Calibrated ages and $(1\sigma \text{ range})$ calibrated ^a	ges and Deposit, dated material ^b , location, sector alibrated ^a						
K _i -4b	W-5121	MN-82-g	Post-1950 A.D.	A.D. post-1950	1969 p flow, Blongkeng, WSW				
F-3	W-3579	MN-209-3a	140 ± 30	1730 (1680–1882)	p flow, quarry, lower Kaliadem-Kinaredjo road, S				
D-1	W-3577	MN-201	160 ± 30	1740 (1674–1817)	p flow, Kaliadem rain gauge (+Golf surface?)				
K _{ii} -3	WW-1619	MN-418	170 ± 50	1750 (1666–1954)	charcoal in ashfall, Banyurejo, Tempel, W				
J-5	W-5118	MN-82-f	< 200	Post-1650	wood in lahar, Tjepagan, K. Bebeng, SW				
H-2c	W-3580	MN-205	200 ± 35	1780 (1661–1805)	p flow, Girikerto, Turi, Sleman, SW, 400 m elev				
M-1b	W-5401	M2NB-1C	200 ± 80	1780 (1647–1819)	p flow, Candi Lumbung, NW				
F-3	W-5385	M15NB-5C	240 ± 80	1660 (1529–1814)	ash cloud surge, Pelem, S				
D-2b	WW-941	MN-304	250 ± 60	1655 (1638–1806)	p surge, charred bamboo, Golf Course subsurface				
I-8	W-5394	M18NB-3W	250 ± 100	1660 (1516–1809)	wood in lahar, Kali Krasak, SW				
M-3	W-5398	M2NB-2C	340 ± 100	~1550 (1446-1660)	tephra?, Candi Lumbung, NW				
N-1	W-5207	RTH-82-C2	340 ± 70	~1570 (1460–1651)	p flow, K. Jueh, Jrakah, NNW				
H-3	W-5843	MN-113i	340 ± 90	~1560 (1449–1657)	p flow, foot of G. Turgo				
E _i -10	WW-1625	MN-400g	360 ± 50	1600 (1460–1638)	lahar, Candi Kedulan, S				
F-6	W-5413	MN-50ee	360 ± 100	~1550 (1441–1654)	p flow, Kinaredjo-Pelem, S				
	(correlates wi	(correlates with W-5378)							
L-3?	WW-2280	SS-1	420 ± 50	1455 (1438–1611)	wood, upper(?) black claystone, K. Sileng, Borobudur				
G-3	W-5764	MM-850711-5	430 ± 150	1450 (1400–1647)	p flow, Kaliurang, S				
G-3	GRDC	SB-KB	470 ± 80	1440 (1410–1487)	p flow, middle of 3, Ngepring, SSW				
F-6	W-5378	M15NB-1C	490 ± 100	1430 (1398–1478)	p flow, Pelem, S				
F-8	W-5377	M14NB-1C	490 ± 100	1430 (1398–1478)	p surge, Pelem, S				
F-7b	W-5386	M15NB-3C	660 ± 100	1300 (1279–1405)	ash cloud surge, Pelem, S				
L-2?	PPNY	Murwanto-SP1	660 ± 110	1370 (1290-1393)	wood, volcanic sediment, K. Sileng, Borobudur				
L-2?	PPNY	Murwanto-SP2	680 ± 95	1370 (1285–1390)	wood, upper(?) black claystone, K. Sileng, Borobudur				
F-20	WW-1617	MN-49NR	710 ± 50	1290 (1279-1303)	ash cloud surge, Pelem, S				
F-20	W-5373	M13NB-4C	740 ± 100	1280 (1221-1379)	ash cloud surge, Pelem, S				
E _i -15	WW-1623	MN-400b	740 ± 50	1285 (1261-1295)	ash cloud surge(?), Candi Kedulan, S				
D-10	WW-1618	MN-210N	790 ± 50	1260 (1221–1284)	ash cloud surge, Kinaredjo, S				
L-3?	PPNY	Murwanto-SS1	860 ± 95	1215 (1163–1251)	wood, upper(?) black claystone, K. Sileng, Borobudur				
N-3	W-5214	RTH-82-C1	880 ± 60	1180 (1046-1229)	p flow, K. Jueh, Jrakah, NNW				
M-14	GRDC	SB-KK	980 ± 80	1080 (994–1186)	p flow, atop Candi Pendem, NW				
F-20	W-5417	MN-50w	1015 ± 100	1020 (899–1161)	ash cloud surge, Kinaredjo-Pelem, S				
	(correlates with W-5373)								
G-14	WK-4406	MN-310b	1130 ± 50	940 (782–982)	lithic p flow, below debris avalanche, K. Boyong				
C-18	W-5198	JPM-1	1200 ± 70	870 (727–956) p surge, road to Deles. nr. K. Woro, SSE					
G-17	W-5392	M1NB-1C	1330 ± 130	680 (618-872)	ash cloud surge, G. Plawangan nr. Pos				

Table	1	(continued)
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Section and unit	Lab no.	Field no.	Age, B.P ¹⁴ C years	Calibrated ages and $(1\sigma \text{ range})$ calibrated ^a	Deposit, dated material ^b , location, sector	
M-17	W-5857	MN-109q	1350 ± 200	670 (541–891)	p surge, Candi Lumbung, NW, just below(?) level of temple floor	
C-19	W-5376	MN-43aaa	1390 ± 120	660 (562-772)	soil, Pajegan, SE	
F-22	W-5375	M12NB-3C	1640 ± 120	420 (256–554)	ash cloud surge, Pelem, S	
	(correlates wi	ith W-5421)				
F-22	W-5421	MN-50t	1700 ± 120	380 (229–532)	ash cloud surge, Pelem, S	
End of known base	ultic products (de	el Marmol, 1989)				
F-28	W-5370	MN-49f	1840 ± 150	220 (19–390)	p flow, Kinaredjo, S	
Somma rim, earlie.	st possible IF no	pyroclastic flows cou	ıld travel east after	r the somma rim was formed		
C-28	WW-1620	MN-420	1900 ± 50	120 (71–147)	p flow, Blorong, Siturejo, Kemalang, SSE	
N-3	W-5163	Jr-1 (RS/RIT)	1900 ± 80	A.D. 120 (25–230)	p flow, K. Apu, Jrakah, NNW	
D-25	W-5379	MN-41b	1990 ± 140	A.D. 20 (B.C. 165–A.D. 193)	p flow, K. Gendol, SSE (mixed magma?)	
C-42	WW-1621	MN-421	2190 ± 50	B.C. 200 (361–172)	p flow, 880 m elev, road to Deles, SSE	
C-42	W-5841	MN-106i	2220 ± 100	B.C. ~260 (391-125)	p surge, Grintingan, SE	
C-42	W-5384	MN-43yy	2460 ± 400	~650 (1004-45)	p flow, Pajegan, SE	
P _{ii} -5	W-5848	MN-300	2590 ± 120	~700 (832–533)	p flow, Cepogo, NNE	
A-6	W-5115	MN-22bb	2870 ± 60	1010 (1265-865)	p surge, Montong, E	
L-3	WW-1624	MN-417a	3430 ± 50	1710 (1851–1676)	wood, base of black lacustrine claystone, Borobudur, W	
N-3	W-5220	RTH-82-C5	3750 ± 80	2140 (2281–1989)	p flow, K. Jueh, Jrakah, NNW	
N-9	W-5217	RTH-82-C3	4260 ± 80	2890 (2917–2703)	p flow, K. Jueh, Jrakah, NNW	
N-8	W-5204	RTH-82-C4	4350 ± 70	2920 (3036–2890)	p flow, K. Jueh, Jrakah, NNW	
E _{ii} -2,3	GRDC	SB-WA	6120 ± 110	5050 (5237-4868)	lacustrine pumice, Watuadeg, 30 km S	
			(same as three	other dates of same unit)		
R-32	WW-1622	MN-425	9630 ± 60	8780 (9000-8618)	p flow, quarry, Sumbung, Cepogo, ENE	

^a Calibration after Stuiver and Reimer, 1993, rounded to nearest 10 calendar years. Values are the 1σ range, in years B.C. or A.D. Where two or more calibrated dates are possible, the most likely is shown; historically impossible ages are excluded. For conversion to years B.P. (before 1950), subtract calibrated A.D. ages from 1950 years and add 1950 years to B.C. ages. For conversion to the Syaka calendar, add 78 years.

^b Dated material is charcoal unless otherwise noted. Outer wood was used where available, but some fragments may be interior wood; therefore, ages should be considered maximum ages for eruptions. All samples were handpicked and pretreated with acid and NaOH to remove modern carbon. Most were run on a conventional gas line; some of the more recent analyses were by the accelerator method. Lab cross-checks have been made to assure comparability of the two.

Abbreviations: p flow, pyroclastic flow; p surge, pyroclastic surge; ash cloud surge, the upper, relatively dilute, turbulent parts of pyroclastic flow clouds that often overflow valleys and leave relatively thin deposits on interfluves.

content, hotter, still-vesiculating blocks and initiation from a greater height or with some initial lateral velocity.

Ash that is elutriated from pyroclastic flows can be emplaced as ash-cloud surge or fall deposits. That which is elutriated from multiple, closely spaced pyroclastic flows can accumulate to tens of centimeters and, in a few instances, several meters in thickness. Some of the thicker deposits of elutriated ash are important stratigraphic markers at Merapi (Andreastuti et al., 2000 – this volume).

3.3. Lahars

Lahars of Merapi, induced by heavy rain on the volcano's slopes, originate from all flanks of the volcano but especially from where recent pyroclastic deposits have burned and buried vegetation cover (JICA, 1980; Lavigne et al., 2000 - this volume). Torrents of runoff incorporate much sediment and, in extreme cases, evolve into debris flows-thick, fast-moving slurries that contain so much sediment that flow is laminar and large boulders are easily rafted. More commonly, Merapi lahars are hyperconcentrated streamflows (as defined by Beverage and Culbertson, 1964), characterized by noisy, turbulent transport of boulders. Debris flows and hyperconcentrated flows of Merapi attain their highest sediment concentrations near the head of the pyroclastic apron source area ($\sim 1000-1200$ m elevation), and become gradually more dilute as they move downstream. By the time they reach 20 km from the summit (elevation 200-300 m), most have deposited so much of their load that they transform into muddy streamflows or "banjirs". Banjirs can also occur when rainfall generates runoff that is heavy but insufficient or too long after an eruption to trigger more concentrated sediment flows.

4. Stratigraphic correlations

Reconnaissance field work, supplemented by limited radiocarbon dating, allows us to present a stratigraphy of Merapi pyroclastic deposits. Fig. 3 locates the composite columnar Sections A–R (Fig. 4), arranged clockwise around Merapi from the east. Uncalibrated ¹⁴C ages are shown in Fig. 4 and Tables 1 and 2; calibrated, calendar equivalents are shown in

Table 1. Units are cited in subsequent text and Table 1 by Section (A-R) and unit number (youngest to oldest) in that particular section. For example, A-1 is the youngest unit of Section A.

The sections of Fig. 4 have been composited from as few as one to as many as six continuous outcrops. In every case, the most complete section of river valley and interfluve was used as a starting point or "master", and units from other less complete sections were added if they could not be identified in the master section. The primary bases for correlationsboth within and between composite sections-are distinctive marker horizons (Andreastuti et al., 2000), sequence of deposits, and, failing other methods, radiocarbon ages. Rapid facies changes and limited primary extent of pyroclastic deposits, combined with subsequent erosion and burial, make unit correlations difficult and often uncertain. Similar lithologies from one eruption to the next, especially during the period of New Merapi, compound the difficulties of correlation.

We found only a few marker horizons that were sufficiently distinctive and extensive to correlate from one drainage to the next. Some represent tephra falls; others are from pyroclastic surges. These marker horizons are indicated on Fig. 4 with the unit abbreviations of Andreastuti et al. (2000 – this volume).

5. Eruptive history

On the basis of field observations, stratigraphic correlations, radiometric dating and morphologic features, we infer a sequence of geologic events at and near Merapi that is summarized in Table 2 and described in more detail in the following paragraphs.

5.1. Erosional formation of Gunung Berjo, Gunung Wungkal

Thirty kilometers southwest of Merapi, hills that rise above the surrounding plain consist mainly of weathered andesite breccias and, in a quarry in Gunung (G.) Berjo, a light-colored, massive, thick andesite lava flow or hypabyssal equivalent. A nearby hill, Gunung Wungkal, is cored by a diorite intrusion and has, on its flanks, upturned, sheared, baked sandstone of Eocene age (Hirayama and Suhanda, 1962;



CONTOUR INTERVAL 200 m

Fig. 3. Locations of composite stratigraphic sections and other places cited in text.



Fig. 4. Composite stratigraphic sections of Merapi pyroclastic deposits, by sector. Arranged clockwise, from the east. Abbreviations: lg, large; sm, small; med, medium; max, maximum; min, minimum; hb, hornblende; px, pyroxene; ol, olivine; mt, magnetite; plag, plagioclase. Wavy contacts are unconformities. Radiocarbon ages are uncalibrated, and are shown in the column descriptions and along the left sides of columns. Three-letter unit labels, e.g. Dls, are for marker horizons identified by Andreastuti et al. (2000 - this volume).



- 2. Gray sandy ash
- 3. Brown soil; locally within it, tan-brown ash-rich soil, overlying indurated gray ash with accretionary lapilli, leaf fossils. May = Tms or Tgs.Nearby, same horizon, dk gray ash w/ one 10-cm block of dark, px andesite pumice). Discontinuous because bioturbated.
- 4. Gray ash, with one horizon of creamcolored and gray pumiceous lapilli
- 5. Gray, slightly indurated ash
- 6. Brown-gray ash-rich soil
- 7. Moderately indurated fine brown soil, with a few white, sugary-textured, dense lapilli
- b. Fine light gray ash, grades into overlying unit
- b. Fine light gray ash, grades into overlying unit
- 10. Discontinuous gray fine ash
- 11. Brown lapilli and ash, soil top
- 13. Discontinuous pods of tan-gray ash in 14. Rusty-brown colored lapilli-fall,
- moderately dense

- 19. Brown soil with a few pumiceous, cream-colored lapilli
- 20. Dark gray coarse sandy ash
- 22. Gray ash with a few lapilli from underlying unit
- 23. Rust-colored lapilli to 2 cm diameter; vesicular, some hb
- 24. Pyroclastic-flow deposit, rich in lithics derived from a lava flow or dome. Some lithics show prismatic jointing; most or all are magnetically aligned

Fig. 4. (continued)



KALI WORO-DELES-BANDAREDJO

- 1. Fine, light-gray ash (1969?)
- 2. Dark brown soil with abundant charcoal bits (from clearing of forest?)
- 3. Light gray fine ash; now, largely brownish soil (layers 3-5=Slk)
- 4. Light gray, indurated, irregularly laminated surge deposit, with accretionary lapilli, Fe staining
- 5. Pumiceous and lithic lapilli, px andesite, most 0.5-2 cm. Rustcolored.
- 6. Fine light gray ash with a few lapilli, one pumice block 12 cm diameter. Some accretionary lapilli and crude strata of granules. Ash cloud surge deposit.
- 7. Px-(hb?) lapilli fall, to 1 cm diameter
- 8. Weathered, yellowish brown ash 9. Granules and small lapilli
- 10. Light gray ash with sparse lapilli to 2 cm diameter
- 11. Small lapilli, with many elongate hb crystals.
- 12a. Gray ash with a few lapilli (together with 12b, =Dls) b. Grav ash, moderately well indurated
- with accretionary lapilli, Fe staining
- 13. Gray-brown ash-rich soil
- 14. Discontinuous layer, well-sorted coarse, brown andesitic ash
- 15. Discontinuous layer, normally-graded gray ash
- 16. Med light gray ash
- 17. Discontinuous fine yellow ash (=regional marker, Andreastuti et al)
- 18. Note: Somewhere near this stratigraphic position, @ 1100-1150 m elev, ashcloud surge deposit sampled by J.P. Lockwood; charcoal 1200 ±70 yr.
- 19. Dark brown, organic-rich soil, with charcoal nr base. 1390 ± 120 yr
- 20. Tan ash (layers 20-22 = Jra)
- 21. Med gray ash
- 22. Brown-black px-bearing granules and lapilli, mostly ~3 mm, a few to 5 cm diameter; also, cream-colored lapilli
- 23. Gray to gray-brown ash
- 24a. Golden brown ash-rich soil
- b. Med-fine, gray to light tan ash
- 25. Pumiceous granules and lapilli in coarse ash consisting largely of ol, plag & augite (salt and pepper appearance). Hb-px lithics, occasionally to 3 cm diameter. Soil at top. (= Pla)26. Gray ash, with brown soil at top
- 27. Tan-brown soil

- 28. Note: On the surface at Dusun Blorong, Desa Siturejo, Kec Kemalang, but at an uncertain stratigraphic position, perhaps near here, there is a breadcrust-bomb-rich pyroclastic-flow deposit, w/ abundant charred logs. 1900 +50 y (sample MN-420)
- 29. Tan-brown soil, bioturbated, formerly gray ash
- 30. Fe-stained, pink-gray ash, many layers, most with accretionary lapilli (layers 30-33 = Tms)
- 31. Fe-stained pink-gray ash, many layers, most with accretionary lapilli
- 32. Yellow-stained granules and pumiceous lapilli
- 33. Gray ash, with only minor Fe staining
- 34. Tan-gray ash-rich soil
- 35. Pumiceous andesite lapilli, up to 3 cm diameter
- (layers 35-38 = Tgs)
- 36. Tan-yellow ash
- 37. Sandy, plag-rich andesitic ash
- 38. Fine gray silty ash
- 39. Med dark brown, organic rich soil, overlying indurated gray ash with numerous root holes, "vesicles"
- 40. Fall deposit, granules and a few distinctive, dense sugary px andesite
- 41. Gray, sandy, overbank pyroclastic-flow deposit with charcoal (MN-422a; for age, see Andreastuti et al, this vol)
- 42. Dome-collapse pyroclastic-flow deposit, clasts up to 80 cm diameter. Mostly coarse sandy matrix, with lapilli and larger blocks, plus charcoal (2190 ± 50 ; 2460 ± 400 yr); soil on top. Ash-cloud surge facies also has charcoal (2220 \pm 100 yr). At MN-421a, has 1-2 cm long augite xls plus smaller hb's.

Fig. 4. (continued)



KALI GENDOL-KLANGON, ABOVE SRAGEN; MERAPI GOLF COURSE

- Pyroclastic-flow deposit at campground; bomb-rich, age=160±30 y. Might correlate with youngest pyroclastic
- flow <u>(#6, Bronto and Sayudi, 1995)</u> at golf course, from 1822 or 1872 eruption.
- 2a. Pyroclastic-flow deposit (=Pyro. flow 5 of Bronto and Sayudi, 1995)
 b. Pyroclastic-surge deposit, fines-poor,
- charred bamboo; 250<u>+</u>60 y. 3. Yellow-tan pumiceous airfall lapilli,
- with dense gray lithics as large as 4 cm diameter.
- 4a. Light gray, fine, clayey ash
- b. Tephra fall; granules and small lapilli
- c. Light-gray fine, clayey ash (4a-c = Slo)
- Dark brown, massive pyroclastic-flow deposit, sand and lapilli, charcoal (= Pyro. flow 4 of Bronto and Sayudi, 1995)
- Pyroclastic-flow deposit (<u>#3 of Bronto</u> <u>and Sayudi, 1995</u>), reverse graded, with charcoal, weathered top
- Pyroclastic-flow deposit (<u>#2 of Bronto</u> and Sayudi, 1995), normally graded, blocky hb andesite lithics in base; puniceous lapilli in center, grading up to dk brown silty-sandy ash, w/ charcoal.
- Pyroclastic-flow deposit (<u>#1 of Bronto</u> and Sayudi, 1995), similar to layer 7
- Tan, stratified ash with giant antcemented concretions ("ant balls," 6 cm dia). Probable surge deposit. Soil on top. (=Dls?)
- 10. (a) Thick, crudely stratified ash with discontinuous layers of lithic and pumiceous lapilli, also with giant ant balls and at least one rip-up clast (c). A lens or second rip-up clast (b) gray, fines-depleted overbank pyroclastic-flow deposit. Age=790±50 y. (= DIs) Note: this unit also had an earlier age, 3040±50 y, that we discard because this unit is in a young part of the overall stratigraphic section of Merapi.
- 11. Fine yellow ash <u>(regional marker of</u> <u>Andreastuti et al, this vol.)</u>
- 12. Gray-brown sandy ash, crudely stratified
- 13. Gray coarse sand and granules
- 14. Andesitic lapilli fall deposit (= Jra?)
- 15. Brown, fine-grained ashy soil16. Gray ash, with scattered px and/or hb xls
- Granular, andesitic ash, with scattered cream-colored pumice lapilli. Lenses out. (= Pla?)

 Pinkish-gray clay with small creamcolored pumice lapilli (layers 18-20 = Tms)

- 19. Gray sandy ash
- 20. Cream-colored pumiceous lapilli and gray lithics; discontinuous layer
- 21. Gray, sticky clay, w/ soil at top. (= Tgs?)

(inaccessible part of section, between interfluve surface and lower part of canyon walls)

- 22. Finely stratified dark brown to black ash, with occasional small plag grains. An aquaclude.
- 23. Ash-rich pumiceous pyroclastic flow breccia (no banded pumice?)
- 24. Pumiceous pyroclastic-flow deposit (no banded pumice?)
- 25. Set of pyroclastic flow and lahar deposits, at least one of which has banded pumice, ol-biotite disequilibrium assemblage, and large hb crystals. Charcoal = 1990 ± 140 yr
- 26. Very coarse, fines-poor lahar or pyroclastic-flow deposit
- 27. Brownish gray pyroclastic-flow deposit

Fig. 4. (continued)

6120

6130



22



CANDI KEDULAN, CANDI SAMBISARI

- Fresh, thinly-bedded sandy sediment**
 Brown soil forming from sandy,
- boulder-bearing lahar deposit, poorly sorted, poorly stratified. 1-1.5 m thick 3. Thin fluvial interbed, sandy
- 4. Gravelly lahar deposit, slightly
- indurated, with subrounded cobbles.* Covered the top of C. Kedulan.
- 5. Thin fluvial interbed
- 6. Lahar* 0.6 m thick
- 7. Thin fluvial interbed
- Lahar at C. Kedulan, 0.4 m thick; fresh gray pebbly sand at C. Sambisari.
 Stratified, coarse fluvial sand, with
- lenses of boulders to 0.5 m dia., 0.1-1.0 m thick. May have two layers.
- Well-indurated lahar deposit, 0.5 m thick, clasts mostly angular pebbles but locally large boulders; matrix=fine sand, silt. May consist of two layers (fig. 6 of Bronto et al, 1997).
- Uncharred palm fibers, 360±50 yr. 11a. Sandy-silty lahar deposit, massive, 0.4 m thick; well-indurated; soil development at top. Overall color of
- this+underlying layer = brown-gray.
 b. Sandy, gravelly lahar deposit, massive, mod. indurated, 1.3 m thick; includes
- scoriaceous blocks and a few leaf fossils 12. Discontinuous 0-4 cm thick fine yellow
- ash (=regional marker ash of <u>Andreastuti et al, this vol.?</u>)
 13. Sandy, granular lahar(?) deposit, with
- Sandy, granular lanar(?) deposit, with scattered hb-plag pumice; poorlysorted, unstratified, friable.* At C. Sambisari, Fe-stained sand
- 14. Well-stratified, cross-bedded fluvial sand and silt, with lenses of coarse sand; charcoal (seeps at base of unit)
- 15. Light-gray silty ash with leaf imprints. Lies on the floor of Candi Sambisari; at or 10 cm above floor of Candi Kedulan. At least 30-40 cm thick at Candi Sambisari; 20 cm thick at Candi Kedulan. When first visited and sampled at C. Sambisari on 12/23/81 it was largely below the water table; when revisited in 9/5/83, during the dry season, the entire area had been cemented in as a storm drain and walkway. Newly excavated at C. Kedulan in 11/97. At C. Kedulan, has small bits of charcoal, 740±50 y. (tentatively, = Dls)
- Ash, with light brown top, incipient soil development (just below level of the floor of C. Kedulan)
- * At C. Kedulan only; equivalents at C.
- Sambisari are mostly floodplain sands.

Fig. 4. (continued)

** At C. Sambisari only

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4

WATUADEG

- 1. Fluvial deposits
- 2. Finely laminated ash-rich sediment;
- $age=6120\pm110$ y on charcoal in soil top 3. Same as above, with soft-sediment
- deformation; age=5840 y on soil top 4. Tertiary (?) tuff, pumiceous, light
- yellow, bedded; soil on top has age=6130 y B.P.
- 5. Pillow basalt (Tertiary)



PELEM/KINAREDJO, KALI KUNING

- 1. Clast-supported, fines-depleted pyroclastic-flow deposit, with both valley-filling and interfluve facies.
- Age="modern" 2. Very fine light gray ash over
- sandy gray ash 3. Matrix-supported interfluve pyroclastic flow deposit(s)(2?), cross- and planarbedding. Ages 140+30; 240+80 y
- 4. Yellow pumice lapilli, to 4 cm diameter
- 5. Pinkish-brown, fine-grained ash-cloud deposit
- 6. Dome-collapse pyroclastic-flow deposit, clast-supported, finesdepleted. Mostly dense andesite; some >1 m diameter. Numerous rootless fumarole pipes, some vapor phase cement, and abundant charcoal. Ages=360+100; 490+100 yr
- 7a. Fine-grained pink ash
- (layers 7-16 = three members of Slk) 7b. Gray, stratified sandy ash with
- scattered lapilli. Some planar-bedded; some cross-bedded. Lapilli dense to pumiceous, max 4 cm diameter. Poorly sorted interfluve pyroclasticflow deposit. Age 660+100 yr
- 8. Surge, limited exposure. Age 490+100 yr 9. Gray pumice and andesitic lapilli, max
- diameter 2 cm
- 10. Coarse crystal-lithic ash
- 11. Lapilli
- 12. Sandy-granular ash
- 13. Salt and pepper granules and lapilli, with moderately abundant px
- 14. Coarse sandy ash
- 15. Lapilli, 2 cm diameter, grading up to "salt and pepper" sand, with px
- 16. light tan ash with scattered lapilli to 3-4 cm diameter; ash-cloud surge deposit(?)
- 17. Brown sand
- 18. Dark gray medium-coarse sand
- 19. Tan-cream colored fine glassy ash, with scattered granules and small lapilli, and bits of charcoal.
- 20. Gray, sandy, fines-depleted, cross- and planar beds, surge-like with relatively coarse, poorly sorted base. Age 710+50; 740+100; 1015+100 yr (together with 19, = Dls)

	9	21	[major color changebrown to gray above] 21. Tan surge, facies of an interfluve
	@- <u>`</u> @		pyroclastic flow? Includes lenses of lapilli. Rootless fumaroles and traces of charcoal at top and bottom of layer;
1640 1700 ^{>}		22	 Interfluve pyroclastic-flow deposit. gray sandy ash and lapilli, fines-depleted, some cross-bedding; matrix supported, lots of charcoal. Age 1700±120;
		23	1640±120 yr 23. Brown, vesicular andesitic lapilli, grapules
		24	24 Fine ash
		25	25. Brown lapilli, vesicular andesite
		26 27	26. Very fine, powdery, light-colored ash
	••••		27. Gray medium sand ash, crystal-lithic,
	• • •	28	plag-rich; incipient soil at top
1840 >			28. Pyroclastic-flow deposit, crystal-rich
		29	andesite, matrix supported. Hb & px
		20	andesite, lapilli to 5 cm. Abundant
		30	charcoal. Age=1840 <u>+</u> 150
	$\sim \sim \sim$	31	29. Coarse lapilli w/ soil; hb-bearing
	· · · · · · · · · · · ·		banded pumice, with small % of lithics
	• •		30. Coarse sandy ash
	•		31. Hb pumice lapilli, most about 1 cm
			diameter, a few up to 6 cm diameter
	•	32	[units 29-31 are from a single eruption]
	• •		32. Brown ash and lapilli, possibly with a
			rip-up of F-34; probably a weathered
			pyroclastic-flow deposit. May have
	•		limited exposures of tephra fall at its
		22	top
		33	indurated [negatibly young out and
		.34	fill?]
		35	andesite, both densities 2-3 cm
	23777277	36	diameter 35. Yellow-brown ash with scattered lapilli
		37	and granules. Possible weathered
		38	pyroclastic-flow deposit.
		20	36. Lapilli
${\bf r}_{\rm eff} = 0$		39	37. Brown ash and lapilli=weathered
	4	40	pyroclastic-flow deposit?
			38. Gray lithic granular ash, andesitic
	22	42	color, max pumice 4 cm; max lithic 3
		43	cm diameter. Grades up into 38.
	2 2	44	40. rine, pinkish gray ash (with soil)
		:	41. Coarse sandy asn, andesitic

ed, pyroclastic-flow deposit (?)

- 43. Discontinuous layer of hb pumice lapilli
- 44. Brown weathered ash (interfluve pyroclastic-flow deposit?)

Fig. 4. (continued)







- G. TURGO KALI TRITIS SLEMAN
- 1994 pyroclastic-flow fan upslope from G. Turgo; ash-cloud surge wrapped around east side of G. Turgo.
- Dark brown soil, with sparse lapilli
 At Desa Girikerto, Kec. Turi, elev.
 560 m, three pyroclastic-flow units.
 Top two sl. weathered, with rounded lithics; age= 200±35 y. Clasts in basal block-and-ash unit are more angular.

3. Well-sorted, fines-depleted, interfluve pyroclastic-flow deposit, with gray, sandy top. Brown, orange, and gray lithic fragments, mostly juvenile px-hb andesite. Age = 340 ± 90 yrs.

- Note: At Desa Wonokerto, Kec. Turi, elev 400 m, a pink block-and-ash flow deposit in quarry. No charcoal found; 9 of 13 clasts have normal magnetic polarity, suggesting hot emplacement.
- Brown sandy ash on top of gray, generally fine-grained ash with leaf imprints and irregular, wavy lenses of sand and silt. Probably ash-cloud surge, but might be fluvial.
- Moderately well sorted, normallygraded, slightly stratified granules and yellow/tan px-hb pumice lapilli to 4 cm diameter. Locally, with crude reverse grading, and a ratio of lithics: pumice = 40:60. With soil at top.
- 6. Fresh, silty gray ash
- 7a Gray ash, w/ brown soil top
- b,c Yellow-tan granules; Gray ash
- d Gray granules, abundant plag xls, minor px; sparse lithic lapilli to 1 cm dia.
- e Gray sand over lapilli (two couplets) f Coarse-fine-coarse ash (triplet)
- g,h Granular ash; Sandy and silty ash
- i Pumice and cream-colored lithic lapilli, to 2 cm diameter; abundant px, hb
- j,k Sandy, overlying granular ash
- l Fine gray silty ash, clean, massive.
- 8a Fine gray ash, elutriated from
- pyroclastic flow. With brown soil top. b Sandy pyroclastic-flow deposit. Locally, coarse, with gray, angular fragments, poorly-sorted, domecollapse pyroclastic-flow deposit. <u>(tentatively, 7a-l and 8a-b = Slk)</u>
- -- break in section -9. Tan silty ash-cloud surge(?) deposit, with sparse giant ant ball concretions and a few lithic lapilli. Magnetization of sparse lithic clasts is marginally coherent. Possibly correlative with
- D-10; also resembles F-21. (=Dls?) 10. Fluvial sands, some sl. indurated, unstratified, up to 1 m thick; others loose, stratified, and few cm or dm thick. Total thickness >5 m.

Fig. 4. (continued)



KALI KRASAK

- 1. 1994 pyroclastic-flow fan upslope from G. Turgo; ash-cloud surge wrapped around northwest side of G. Turgo.
- 2. Yellow-brown, matrix-supported, indurated pyroclastic flow or lahar deposit. Heterolithologic, with rootless fumaroles or water escape pipes.
- 3. Brown, matrix supported breccia, with cross bedding and planar lamination. Pyroclastic flow or lahar deposit.
- 5. Fines-depleted, well-sorted lapilli fall
- 6. Yellowish-brown, matrix-supported, partially indurated pyroclastic flow or lahar deposit
- 7. Poorly-sorted lahar, massive, matrix supported, with shredded, uncharred wood at top.
- 8. Poorly-sorted, massive lahar deposits (5 or more). Abundant shredded wood, age 250 ± 100 yrs
- 9. Black, partly lithified tephra, ash, soil 10a Tephra: coarse sand, granules; 50% lithics (9a-e = Slk?)
- b Tephra: pumiceous lapilli in med size sand
- c Tephra: coarse sand, granules; 50% lithics
- d Tephra: pumiceous lapilli, as above
- e Tephra: sand, granules, as above 11. Brown, weathered, matrix supported pyroclastic-flow (?) deposit
- 12. Gray, clayey ash
- 13. Brown, weathered, matrix supported pyroclastic-flow (?) deposit
- 14. Lahar, > 4 m thick, poorly sorted (not to scale)



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1 meter

KALI BATANG - KALI BEBENG

- 1. Lahar deposit, poorly sorted, rounded clasts
- 2. Lahar deposit, poorly-sorted, rounded clasts
- 3. Indurated, well-stratified fine silt with abundant accretionary lapilli. Ashcloud surge deposit?
- 4. Reversely-graded, poorly-sorted breccia, with red, friable sandy matrix, indurated near top. Wood is charred near base of unit; partly charred near top.
- 5. Lahar deposit, with charcoal and uncharred wood. Age < 200 yrs.
- 6. Normally-graded tephra fall, med coarse lapilli to coarse sand, with weakly developed soil at top.
- 7. Normally-graded tephra fall, med coarse lapilli to coarse sand, with partly charred vegetation at base of tephra.
- 8. Matrix-supported dome-collapse pyroclastic-flow deposit
- Note: Substantially older units of G. Ukir, G. Tugel, and G. Guling (all of the Gendol Hills) are cut by K. Batang but are described in section K_{ii}.







GUNUNG GENDOL (GENDOL HILLS)

- Young lahar deposits surrounding the hills. Lahars in 1969 traveled down K. Senowo, K. Lamat, K. Blongkeng, K. Putih, K. Bebeng, K. Batang, and K. Krasak,; larger lahars in 1931 traveled down the same rivers, and, by overflowing an old channel of K. Batang south of G. Guling, shifted flow to its current channel north of G.
- Guling, past G. Tugel and G. Ukir.2. Lithic andesite ash, medium sand to granular, several layers, each several cm thick.
- (exact stratigraphic level uncertain) Discontinuous, 0-20-cm-thick bioturbated fine ash (b), below fluvial sediments (a) and above a deep soil developed on older stream gravels (c). Dusun Barongan, Desa Banyurejo, Kec Tempel, elev 170 m. Charcoal in the fine ash layer gave an age of 170±50 y (sample MN-418).
- 4. Tuffaceous silts and sandstones, pumiceous, with leaf fossils. Gray, relatively fresh, dipping 15° at best outcrop, SW corner of G. Ukir. Age uncertain. This <u>might</u> be the plantrich "blast deposit" described by Camus et al (this vol) but it is unlike that seen by us elsewhere around Merapi; alternatively, it might be Tertiary in age (see K-Ar age, below).
- 5. Lavas and indurated pyroclastic-flow breccias of the Gendol Hills. Fresh outcrops are scarce, but those seen include (from SE to NW): G. Guling, hb-andesite pyroclastic-flow breccia, excellent exposure, NO jig-saw fractures, paleomagnetic vectors in clasts uniformly normal polarity, K-Ar age, 3.44+0.09 Ma; G. Tugel, massive, slightly sheared hb andesite lava, reversed polarity, NO jig-saw fractures; G. Ukir, hb-px andesite lava; G. Grogolan," monolithic hbandesite lahar(?) breccia; G. Kremeng, behind Chinese cemetery, weathered hb-andesite float; G. Pring, in situ, orthogonally jointed (NOT jig-sawfractured), spheroidally weathered andesite lava, reversed polarity; G. Sari, G. Pugulan, as at G. Pring, plus possible lahar breccia w/ silica cement. (not to scale)



Fig. 4. (continued)



CANDI DUWUR-CANDI LUMBUNG-CANDI PENDEM

1a. Accretionary lapilli ash

- b. Brownish-gray, coarse, indurated sandy pyroclastic flow breccia. Matrix supported, heterolithologic, with both dense and semi-pumiceous fragments to 15 cm diameter. Clasts are magnetically aligned. Charcoal = 200
- ± 80 yr B.P.; no uncharred wood.
 2a. Coarse sand-granular tephra fall. Sub-spherical pumice granules, lapilli to 4 cm diameter; avg=granules.
- b. Fine sandy ash
- c. Coarser, fines-depleted surge(?) deposit; dune-bedded gray sandy ash
- Dark brown clayey soil developed on sandy ash with charcoal. 340 ± 100 yr
 Brown clayey ash with weathered lapilli
- Brown chayey ash with weathered laphing to 4 mm diameter
 Brown coarse sandy ash with granules
- Brown coarse sandy ash, with granules and dark, dense lapilli to 1 cm dia
 Gray, moderately well indurated ash
- with sparse pumice lapilli. 3 cm of brown soil developed on top.7. Semi-cemented gray ash with lithic
- granules (locally grain-supported), Festaining, and doubtful accret. lapilli
- 8. Silty gray ash with sub-mm scale convolutions in layering
- 9. Reddish gray fines-poor lithic andesite fall deposit
- 10. Fine, laminated gray ash, possibly with accretionary lapilli
- Reddish lapilli to 3 cm dia in silty ash matrix, with small oxide and hb grains
 Fine grained ash-cloud surge(?) deposit,
- grading down to dk brown massive clayey bed with lapilli to 1 cm dia.
- 13. At least 8 ashfall and ash-cloud deposits; indurated, reddish gray.
 -- break in section --
- Pyroclastic-flow deposit that buried Candi Pendem. Age=980+80 ¹⁴C y. Strat. correlation based on ¹⁴C age.
 -- break in section --
- 15. Coarse tephra fall; unconsolidated granules and lapilli. Gray, normally graded, with hb-px pumice (max diameter 4 cm) and dense, darker lithics (max diameter 3 cm). Lower part of bed is slightly lighter-colored than upper part.
- --- Level of the floor of Candi Lumbung probably near here, though it could be as high as unit 9.
- 16. Brown silt with fine laminae (surge?)
- Unconsolidated brown silt with mm to cm scale laminae. Pyroclastic surge deposit with lapilli to 1 cm diameter. Charcoal 1350 <u>+</u> 200 yr





Fig. 4. (continued)



1 meter



1. Granular andesitic lapilli, with soil

- 2. Grav ash with 15 cm soil at top
- 3. Brown weathered granule + lapilli tephra
- 4. Thin gray ash layer grading up to thicker
- brown soil with scattered lapilli
- Gray-brown soil with small granules, hbpx lapilli (fresh if dense; soft and leached if pumiceous) plus patches of gray ash
- Granular tephra with dark brown soil top
 Reddish-brown soil with scattered lapilli, grading downward to poorly-defined beds of med sand, coarse sand and granules, and at the base, fine sand
- Med brown soil with weathered lapilli
 Granular tephra with slightly pumiceous hb-px lapilli; less abundant dense lapilli. Max pumice=3 cm; max lithic 1 cm.
- 10. Soil with a thin horizon of lapilli
- 11. Tephra; slightly pumiceous hb-px lapilli and less abundant dense lapilli. Slightly coarser than overlying tephra

12a Light brown soil with a few lapilli

- b Fine gray ash, grading into units above and below
- c Brown, fine silty soil
- 13. Gray ash
- 14. Brown clay-rich soil, slippery, with tiny orange spots from weathered granules and lapilli

15. Gray ash with normal grading from med coarse sand to silt size grains
16. Brown call with coarse grache from calls

16. Brown soil with orange specks from relic granules



17

- 17. Gray, coarse ash + few lapilli; salt and pepper appearance from variable weathering of pumiceous and dense grains
- 18. Gray-brown soil with sparse, weathered granules
- 19. Bright rusty orange friable lapilli
- 20. Grayish tan clayey soil
- 21. Very dark brown soil with few oxidized lapilli, developed on brownish gray soil with small weathered granules
- 22. Coarse, rust-colored lapilli fall bed 23. Grayish-tan soil with sparse light-
- colored pumiceous lapilli 24a Dark soil with few oxidized lapilli
- b Gray sandy ash, progressively less oxidized with depth
- c Gray sandy ash, relatively fresh, finegrained
- Alternating airfall ash and lapilli layers, most deeply weathered with soils. Multiple sets; >17 m thick.
- 26. Explosion-type pyroclastic-flow deposit, with black, basaltic andesite or andesite breadcrust bombs. Reddish brown soil developed on top. Probably >4 m thick.

****Ed note-- Some or even many of these beds could be from Merbabu; this section is on the slope of Merbabu.







CEPOGO, NW + downstream of K. Kenting bridge

- Indurated pyroclastic flow(?) deposit, with scoria, some augite crystals. Stratigraphic position ambiguous.
- Coarse gray sandy ash; probably an overbank pyroclastic-flow deposit.

-- break in section; stratigraphic position of next unit uncertain --

3. Indurated, 3 to 5-m-thick surge(?) or fine-grained lahar(?) deposit with abundant bamboo molds, leaf molds. Wood was not charred and thus not preserved. Relatively young, because no other deposits found on top. (<u>=the</u> <u>so-called "blast" deposit of Camus et</u> <u>al, this volume) (possibly = Tms or</u> <u>Tgs?)</u>

-- break in section

- Coarse laharic breccia; locally brown and indurated, with soil at top; elsewhere gray, unconsolidated. Magnetic vectors in clasts are random.
- Unconsolidated pumiceous hb andesite pyroclastic-flow deposit. Gray and white banding in pumice, probably as function of vesicularity. Abundant charcoal, 2590 ±120 yr BP.
- 6a. Px-rich lava flow, upper of 2 flow units, separated from lower unit by flow rubble
- b. Px-rich lava flow, lower of 2 flow units. Relatively fluid flow that reached 5 km from G. Bibi or 8 km from G. Merapi.

Fig. 4. (continued)

Fig. 4. (continued)

	Q		
	7.11	1	WONODJOJO
			1. Soil, with some light-colored ash but no
			distinct ash layers (2 m thick)
		ľ	rich, dark gray, several layers (=Jra)
			3. Lapilli + granules, fines-poor, with
			euhedral px; salt/pepper-like $(=Pla)$
	7,7,7,7		4. Planar-bedded, fine, light-gray ash with abundant accretionary lapilli: soil top
Jra		2	5. Hb pumice lapilli, with some gray/white
Pla	~~~~	3	banding (units $5+6$ together = Tms)
	THY		6a. Gray ash with soil at top
		4	 b. White and gray banded pumice lapilli 7. Brown soil with scattered lapilli
	لوبنينونه	5	8. Gray, med-coarse sandy ash
Tms		6b	9. Brown soil with a few hb-dacite pumice
	in the second	7	lapilli as large as 4 cm dia near top
	-a	8	10. Fine, finely-bedded, indurated, sometimes
		9	11. White, slightly weathered pumiceous
Tgl		10	lapilli, up to 6-cm-dia. Hb-rich, with
	ستستن	11	possible compositional banding
		12a	$\frac{(\text{layers 9-11, together, } = Tgl)}{12n}$
		12b	b. Indurated gray ash. in which layers of
	-1-1-		accretionary lapilli ash alternating with
	1. C. C.	13	structureless ash. Fe-stained
			13. Light brown silty soil, with lapilli throughout (colluvium or overbank
	سننت	14	pyroclastic-flow deposit)
		15 16	14. Pinkish-gray indurated ash with lapilli
	-{-{-	17	near top; Fe-staining
	にここ		15. Fe-stained soil with few white lapili
		18	17, 18. Light gray fine ash, w/ fragment of
	تهجمها	19 20	dense, glassy, flow-banded andesite with
		21	sparse Fe-Mg minerals; soil top
	-7		19. Gray, inducated, line ash, with lapilli to
	0.5	22	20, 21. Slightly indurated gray ash, reverse-
	لنتعتبنا	23	graded from silt to med sand; soil top.
		24	22. Light brown silty soil; ash-rich
	<u></u>	25	and dense lithics (to 2 cm dia)
	5 5 5	26 27	24. Tan ash-rich soil, with minor lapilli
	<u>x i i i</u>	28	(ash cloud deposit?) (0.65 m thick)
		29	25. Indurated light gray fine-sandy ash
		30	discontinuous soil on top
Kjn		31	28. Indurated light brown soil
	EFE	33	29. Sand and lapilli to 1 cm diameter, plag-
		34	rich with minor px, minor charcoal
			30. Yellow-tan soil with white pumiceous lapilli at top, max 4, avg 1 cm diameter
		35	31. Fine gray ash, with pink accretionary
	·		lapilli, sandy laminae, and spots of Fe-
			oxide staining. Surge deposit? $(=Kin)$
	т		33. Brown-tan silty soil
			34. Clayey, laminated fine ash, with Fe-

1 meter

ated fine ash, with Festained bedding planes

		35. Pinkish or violet-grav silty ash
	36	36. Light gray ash. Finely laminated. locally
		indurated, with accretionary lapilli. White
in second	37 38	pumiceous lapilli at top. $(=Jar)$
hand	39	37. Light gray, indurated sandy ash
1.3. 7.5	40	38. Bright orange silty ash
	41	39. Rust-spotted gray ash
	42	40, 41. Alternating gray ash and coarse
	43 44	sand or granules, w/ Fe-staining along
C C C	45 46	A2 Top siller och with source levilling to
12-2-2-1-1	40 47	42. I an slity asn, with sparse lapilli at top.
550	•	43 Fine gray ash
111	19	44. Tan silty ash with white lanilli at ton
	40	45. Grav. med-fine sandy ash
12	49	46. Tan, silty soil, with white lapilli at top.
	40	Ash-cloud surge deposit?
	50	47. Creamy-white weathered or altered hb-
		px dacite(?) pumice lapilli
	51	48. Tan-brown silty soil with rusty flecks
		49. Fine gray ash
1	52	50. Tan-light gray (or pink?) silty ash with
		pockets of underlying ash
-1-1-1	53 54	51. Discontinuous light gray fine sandy ash
	55	52. Tan-pinkish gray silty ash-cloud surge
(56	deposit, with a lew sparkling white
	57	cm in diameter + tiny black yla
	59	53. Discontinuous layer of gray silty ash
3-25	60	54. Brown silty soil, with minor clay +
D. C. X		specks of plag, small pumice granules
• • •	61	55. Dark gray, angular andesitic lapilli
	01	56. Gray brown silty soil with layer of
	62	yellow lapilli
ليبجينهم		57. Discontinuous gray ash and lapilli
1 3 3 3	63a	58, 59. Gray fine sandy ash, soil on top
	63b	60, 61. Indurated dark gray ash, med sand,
		with blocky fractures resembling lapilli.
	63c	62 Gray ash normally graded from assure
		to fine sand with soil at top
	64	63 Sandy gray ash, brown soil at top
	65	64. Tan clavey ash with weathered plag
		65. Fresh gray, med sandy ash
(\$) (\$)	00	66. Andesitic scoria fall. Grayish brown
L.C.J.	67 68 60	coarse sand and granules, + a few lapilli to
-1-3-1	70 03	1 cm diameter. Mostly fresh, but with a
		few cream-colored weathered lapilli
1.5.5.5.5	72a	67. Pinkish(?)-brown clayey soil, with
		pockets of gray ash and weathered lapilli
		68. Fine light gray, clayey ash
		70 Fine light group pink eleven ask
• • • ·		71 Dark brown claver soil with senttened
	72b	weathered lapilli
· · · ·		(minor gap in section)
· · ·		72a. Gray breccia with sl. rounded cobbles in
· •••		(hydrothermally altered?) matrix.
		b. Probable pyroclastic-flow deposit, dark
		gray, unconsolidated, abundant angular
		fragments of px andesite. Grades into
		overlying, altered (?) unit

R 5 2 - Floo Candi ς 3 4 5 6 9 10 11 12 13a 13b • • 13c 14 1 meter



Fig. 4. (continued)

Calendar van Bahar del Marmol Wirakusumah Camus et al. Andreastuti et al. This paper ages Bemmelen (1984)(1989)et al. (1989) (2000 - this)(2000 - this)volume) (1949)volume) NEW MERAPI^b 2000 A.D. New Merapi Summit lavas New Merapi Young Merapi Historical Merapi - 1888 A.D.^a -– 0.5 ka – Pasarbubar^c - relatively weak 20th century Kepuhario eruptions, mostly dome growth and K. Kuning and G. Bibi Recent Merapi Selokopo collapse Selokopo lavas (Sambisari gp) Deles - many explosive eruptions, alternating with dome growth and collapse - small debris avalanche - formation of (new?) Lake Borobudur - 1006 A.D.^d - 1006? A.D.^d -1000 A.D. - more large explosive eruptions - 928 A.D.^{d,e} Mataram civilization - 928 A.D.^e -Muntilan Selo becomes silent Jrakash - 732-928 A.D. major temple Olde Merapi Batulawang construction lavas Old Merapi - c 1.6 ka^b -- large explosive eruptions - early growth of new Merapi Plalangan 0 A.D. – 2 ka – Temusari OLD MERAPI^b Tegalsruni - final even: somma-forming collapse Nglencoh and debris avalanche Middle-aged Ngrangkah - youngest pyroclastic-flow deposits E side^b Merapi Tosari (Gumuk gp) Kujon - continued growth of the Old Merapi Jarak Bakalan 1000 B.C. $- c 3 ka^{b} -$ Collapse Kadisepi - impounding of an early Lake and blast Borobudur (?) Old Merapi Sumber - Gunung Bibi Ml2 lavas 5000 B.C. Merbabu Very Old Merapi – 8 ka – tephras G. Turgo. G. Turgo Ml1 lavas - oldest dated deposits of Old Merapi G. Plawangon G. Plawangan G. Turgo, Ancient G. Bibi G. Plawangan Merapi PROTO-MERAPI Pleistocene G. Turgo, G. Turgo, G. Plawangan G. Plawangan – c 60 ka –

Pre-Merapi G. Bibi, >400 ka

Table 2 Several interpretations of the broad outline of Merapi stratigraphy. Ages are in calendar years

Table 2 (continued)

Calendar ages	van Bemmelen (1949)	Bahar (1984)	del Marmol (1989)	Wirakusumah et al. (1989)	Camus et al. (2000 – this volume)	Andreastuti et al. (2000 – this volume)	This paper
Tertiary	Old Andesite Fm. ^f (incl. Menoreh Mountains)			G. Gendol			MENOREH MTNS. G. Gendol (one K–Ar age, 3.44 Ma; one paleomagnetic reversal)

^a Based on colonial and postcolonial records.
 ^b Age determinations by M. Rubin and J. McGeehin, USGS, Reston, and D. Trimble, USGS, Menlo Park.

^c These are named marker horizons, both fall and widespread surge units.

^d Based on misinterpretation of old inscriptions, after van Hinloopen Labberton (1922) and van Bemmelen (1949).

^e Based on modern interpretation of inscriptions (e.g. Dumarçay, 1986; Miksic, 1990).

^f Age based on stratigraphic position between paleontologically dated sediments. Various workers have estimated ages from Eocene to Miocene.

Rahardjo et al., 1977). We do not know the age of this intrusion, except that it is post-Eocene.

G. Berjo, G. Wungkal and a half dozen other hills in this cluster have shapes and locations that at first suggested distal debris avalanche deposit from Merapi, but the massive, unbrecciated, in situ aspect of andesite in G. Berjo and the intrusive relation and Eocene age sandstone of G. Wungkal argue against such an origin. Instead, we infer that these are erosional remnants of some volcanic and sedimentary terrain of early Tertiary age; presumably, the erosion occurred from mid-Tertiary to the present.

5.2. Erosional formation of Gunung Gendol

Gunung Gendol and nearby Gunung Sari, Gunung Ukir and several other hills, known collectively as the Gendol Hills, lie 20 km west–southwest of Merapi (Fig. 4, column K_{ii}). Rising to as much as 150 m above the surrounding rice paddies, the hills consist of deeply weathered hornblende- and pyroxene-andesite. Small patches of pumice-rich, leaf-imprinted tuffaceous sediments, some dipping 15° to the northeast, are preserved near the base of at least two hills.

These hills were judged by van Bemmelen (1949) to consist of lahar deposits from the older Merapi cone, crumpled into hills by the gravitational collapse of the western flank (Fig. 2). "The folding up of the west foot formed a threshold in the Progo valley, so that upstream a lake temporarily originated, which flooded the area downstream of the temples Borobudur, Pawon and Mendut" (van Bemmelen, 1956, pp. 33–34). Citing archeological sources, van Bemmelen supposed that collapse of Old Merapi occurred in 1006 A.D. Berthommier (1990) and Camus et al. (2000 – this volume) reinterpret the Gendol hills to be hummocks of a Mount St. Helens-like debris avalanche.

What observations can be used to evaluate these interpretations? These hills occur where a westwarddirected debris avalanche from Merapi might have come to rest, and, at first glance, are suggestive of debris avalanche hummocks. However, we believe that a set of observations favor an alternative interpretation, that these hills are erosional remnants of pre-Merapi volcanic terrain:

• The Gendol Hills consist of hornblende- and

pyroxene-andesite that is more similar to rocks of the Menoreh Mountains, 7 km to the west, than to those of Old Merapi, and are more deeply weathered than any rocks from Old Merapi. Although lithologies are variable in all three complexes—Old Merapi, Gendol Hills and Menoreh Mountains—an abundance of andesite with slender hornblende laths in the Gendol Hills and Menoreh Mountains suggests a close relation between the latter two.

• A new K-Ar age, from an unusually fresh outcrop of hornblende andesite on the south side of one of the hills, G. Guling, is 3.44 ± 0.09 Ma (Lanphere, written commun., 1998). This is considerably older than any Merapi rocks that we have dated, and considerably older than the oldest age that Camus et al. (2000 – this volume) report for Merapi (0.04 Ma).

• None of the hills, as best as we can tell, have jigsaw brecciation and block facies/matrix facies relationships that are characteristic of debris avalanche deposits. Camus et al. (2000 – this volume) report such brecciation and textures, but every fresh outcrop that we have examined lacks such textures. Good outcrops in the Gendol Hills are scarce, and we think we have found most if not all of the outcrops suitable for textural examination. Especially good outcrops occur along the south side of G. Guling (primary pyroclastic-flow breccia) and on the west side of G. Pring and the south side of G. Tugel (massive or orthogonally-jointed lavas).

• None of the hills, as best as we can tell, have rotated or otherwise disturbed paleomagnetic vectors. The lavas of G. Pring and G. Tugel both have reversed magnetic polarity. Paleomagnetic orientations of all clasts in the dated G. Guling pyroclastic-flow breccia are perfectly consistent and normal.

• If these hills, up to 150 m high at 20 km distance from Merapi's summit, were debris avalanche hummocks from Merapi, there should be other, nearby hummocks, traceable with diminishing height (increasing degrees of burial) toward Merapi. With the possible exception of G. Gono, a small, 20m-high hill, 13 km west of the summit, we know of no other candidates for debris avalanche hummocks. This last argument is not a strong one, because rapid sedimentation on the alluvial apron of Merapi can occur at rates of meters or even tens of meters per 1000 years, and that sedimentation could have buried smaller hummocks. The sum of these observations suggests to us that the Gendol Hills are erosional remnants of pre-Merapi volcanoes, and are not from a landslide-like "slip faulting" or debris avalanche of Merapi.

5.3. Growth and destruction of Proto-Merapi

Two prominent, steep-sloped hills, Gunung Plawangan and Gunung Turgo, rise as high as 375 m above mostly pyroclastic deposits of the south flank of Merapi (Fig. 4, columns G and H). The hills consist of variably weathered, mostly basaltic lava flows, and were apparently a single mass that is now bisected by Kali Boyong (Fig. 3). Berthommier et al. (1990) considered these hills to be a basaltic flank vent of an old Merapi, and obtained a U-Th age of 40,000 \pm 18,000 years for one of its basaltic lava flows. However, we doubt that these hills are a flank vent because we found no dikes, plugs, nearsource spatter or cinder or other evidence of a vent. As an alternative interpretation, we suggest that these hills are high-standing erosional remnants of the earliest cone of Merapi, which we call "Proto-Merapi", pre-dating van Bemmelen's "Old Merapi" (Table 2). Their lavas dip slightly to the north, toward the modern Merapi, so these hills might be blocks that rotated slightly during gravitational failure of Proto-Merapi (Voight, written commun., 1997).

How did these hills develop such steep faces on both their upslope and downslope sides? And where is the rest of proto-Merapi? Normal hillslope and fluvial erosion was surely at play, especially in shaping the steep side-faces of these hills. An origin as blocks of gravitational failure of proto-Merapi, as suggested above, could also have left steep slopes. No other deposits of such a collapse are known, but they could easily have been buried by later sediments.

5.4. Growth of Old Merapi

The eastern flank of Merapi is deeply dissected and its canyons, plus a somma rim that opens to the west, expose intercalated lava and pyroclastic deposits (Fig. 4, columns A, B, O–R). These deposits constitute an Old Merapi, named by van Bemmelen (1949). Lavas of the upper parts of Old Merapi were called Batulawang lavas by Bahar (1984); intercalated pyroclastic deposits can simply be called pyroclastic deposits of Old Merapi. Compositions of Old Merapi or Batulawang lavas range from basalt to andesite (Bahar, 1984; del Marmol, 1989).

The oldest known deposit of Old Merapi is a breadcrust-bomb bearing pyroclastic-flow deposit in Sumbung, Cepogo (Fig. 4, R-32, age = 9630 ± 60^{14} C y). The next oldest known deposits are reworked pumiceous silt overlying much older pumice tuffs and pillow lavas, 30 km south of the summit at Watuadeg, between the villages of Nogotirto and Jogotirto. Charcoal from paleosols on these two silty deposits, and that immediately below, yields essentially identical ages of about 6000 ¹⁴C y. Because the material is fine grained, it could conceivably be reworked tephra of a more distant volcano, but Merapi is the closest volcano to this site and the only volcano in this drainage and often produces silts like these.

Continued explosive eruptions of Old Merapi produced a several-hundred-meter-thick pyroclastic apron around Merapi, within which occur a wide variety of pumice-, breadcrust-bomb- and lithic-rich pyroclastic-flow deposits. Details of explosive eruptions of Old (and New) Merapi are being studied by Andreastuti et al. (2000 – this volume).

Lavas that form the bulk of the eastern and northern slopes of Merapi are also of Old Merapi. We cannot recognize any systematic difference between the eruptive style or compositions of Old Merapi and New Merapi, except that Old Merapi products include basalts as well as dominant andesite, while basalt is apparently absent in New Merapi (del Marmol, 1989).

5.5. Growth of Gunung Bibi

A small but conspicuous cone- or dome-shaped hill, Gunung Bibi, lies high on the northeast flank of Old Merapi. Several samples from G. Bibi are phenocrystrich basaltic lavas that contain more hornblende than augite, though one young basaltic andesite lava (52.7% SiO₂) from G. Bibi contains nearly 12 vol% large augite crystals and no hornblende (del Marmol, 1989). Immediately west of Cepogo (Fig. 3, near P) and 5.5 km NE of G. Bibi, 8 m of coarse, poorly sorted, deeply weathered basaltic scoria fall deposits (P_i-15,16) contain abundant large (up to 1 cm long) euhedral augite crystals. A scoriaceous augite-rich pyroclastic-flow deposit (P_{ii}-1) lies immediately below the augite-rich scoria fall and may be coeruptive with it. Although the scoria is distinctive enough to be easily recognized elsewhere, we have not found it elsewhere around Merapi. Poor sorting and coarse fragments (up to 20 cm dia) suggest a nearby source, possibly G. Bibi; the pyroclastic-flow deposit could have originated from G. Bibi though topography would also allow an origin from G. Merbabu (next large volcano to the north). Gunung Bibi was interpreted by Berthommier et al. (1990) as an old, pre-Merapi feature because a K–Ar age was 0.67 Ma. The dated sample was altered, so we are skeptical about this age. Instead, we interpret G. Bibi to be a vent that erupted through and built itself on the upper flank of Old Merapi.

5.6. Impoundment of Lake Borobudur

At least 20 m of fine-sand to clay sediments extend up the Kali Progo plain from a point west-southwest of Merapi (Purbohadiwidjojo and Sukardi, 1966; Nossin and Voûte, 1986a,b; Murwanto, 1996) (="Alluvial plain of Borobudur", Fig. 2). The best exposures that we have seen are along Kali Sileng, tributary to Kali Progo. None of these deposits are classic white diatomaceous lake sediments; they consist of relatively fine clastic material, locally with fine-scale stratification. Two main units are recognized: a thicker, black to gray sequence deposited and kept in a reducing environment, overlain by a thinner yellow-brown sequence that was, either at deposition or subsequently, in an oxidizing environment. Wood from near the base of this sedimentary pile yielded and age of 3430 ± 50^{-14} C y (Fig. 4, unit L-3). Wood from the upper parts of this lacustrine sequence yielded ages of 860 ± 95 , 680 ± 95 and 660 ± 110^{-14} C y (Fig. 4, unit L-2; dates from Murwanto, 1996). The widely disparate ages might indicate: (a) a long-lived lake, first formed \sim 3430 ¹⁴C y B.P.; (b) two lakes, one formed and filled \sim 3430 14 C y B.P. and another formed and filled in the same area $\sim 860-660^{-14}$ C y B.P. $(\sim 1200-1400 \text{ A.D.})$; (c) one lake, formed and filled during the same, 1200-1400 A.D. period, into which a piece of much older wood was carried; or (d) a systematic and serious discrepancy between ages from the two laboratories involved. (a) and (b) are possible; (c) is less likely because the dated

wood was not abraded as one might expect in erosion and re-transport from Merapi. We have no reason to suspect (d), but we have not run split samples through both labs to confirm their consistency. Hypothesis (b) is similar to events at the foot of Mount Pinatubo, Philippines: a lake at the foot of Pinatubo that was impounded by lahars in 1991 has been filling with sediment since that time, and discovery of an ancient canoe in the same location suggests that a lake had formed after the previous eruption, too, and had been filled in before modern settlement (Umbal and Rodolfo, 1996).

Two blocking agents are possible: rapid volcaniclastic sedimentation (as described, for example, by Umbal and Rodolfo, 1996) or a debris avalanche dam (examples compiled by Siebert et al., 1987; Costa and Schuster, 1988). If Kali Progo itself were blocked, a relatively effective blocking agent such as a suddenly emplaced debris avalanche seems more likely.

Nossin and Voûte (1986a,b) argued that any event that dammed Kali Progo and formed Borobudur Lake must have occurred "long" ago, because the lake had to fill with sediment, breach, and then the whole area had to be tectonically uplifted to create terraces that are cut in the lake deposits. However, experience with rapid sedimentation in impounded lakes at Pinatubo (cf. Umbal and Rodolfo, 1996) suggests a much simpler scenario: a lake can be impounded, filled and breached within only a few years to decades, perhaps centuries, and terraces form mainly during re-incision back down to base level. Tectonic uplift need not be invoked.

5.7. Debris avalanche failure of Old Merapi

The most distinguishing characteristic of Old Merapi is a prominent somma, open to the southwest, similar to those which form from massive collapse of stratovolcanoes (for example, at Mount St. Helens; see Siebert, 1996). Can such a collapse be confirmed and, if yes, when did it occur?

Starting with the second question first, the youngest pyroclastic-flow deposit that we found on the east or southeast side of Merapi has an age of ~1900 ¹⁴C y B.P. (unit C-28; Table 1, Fig. 4). Pyroclastic flows apparently continued on the south and west (e.g. units F-22 and F-28, Table 1, Fig. 4, 1640 \pm 120, 1700 \pm 120 and 1840 \pm 150 ¹⁴C y B.P.). If the vent



Fig. 5. Debris avalanche deposit, Kali Boyong valley. Megaclasts of brecciated lava and stratified pyroclastic material occur in a matrix of brecciated smaller clasts, sand and clay.

after somma-forming collapse was far below the somma rim, as at Mount St. Helens today, and the rim blocked subsequent pyroclastic flows, we can infer that collapse to the west and blockage of further pyroclastic flows to the east became effective sometime $\sim 1900^{-14}$ C y B.P.

To confirm such a collapse, we should find debris avalanche deposits of ~ 1900 years of age. Frustratingly, we have not found any, and suggest three explanations:

(a) the avalanche was too small to produce a significant number of hummocks;

(b) the avalanche was too weak or wet to form discrete hummocks and, instead, formed the equivalent of a lahar sheet; and

(c) any hummocks that did form have been subsequently buried by rapid sediment accumulation around the base of Merapi.

Explanation (a)—of a small avalanche—is inconsistent with the large, 3 km diameter of the somma rim. Explanation (b)—of a wet, soupy avalanche—is suggested by debris avalanches that transformed to lahars at Mount Rainier (Crandell and Waldron, 1956; Scott et al., 1995), Mount Egmont (Palmer et al., 1991), Galeras (Banks et al., 1997), and other volcanoes. Merapi lacks the degree of hydrothermal alteration and the glacial caps of Mounts Rainier and Egmont.

Explanation (c)—burial—seems the most likely. Merapi produces 10^6-10^7 m³ of sediment each year, which would bring between 10^9 and 10^{10} m³ of sediment per 1000 years onto the west and southwest slopes, with potential accumulation of between 2 and 20 m of sediment averaged over the area of 500 km². Some temples as tall as 10 m (Candi Sambisari, Candi Lumbung) were buried in ≤ 1000 years; about 2.5 m of Candi Kedulan was buried in ~400 years. Explanation (c) is corroborated by apparent absence of any deposits of ≥ 1900 years B.P. on the west flank of Merapi. Apparently, all deposits of that age could now be buried beneath younger debris.



Fig. 6. Candi Sambisari, near the Yogyakarta airport, buried by ≥ 40 cm of fine ash and about 6 m of fluvial sediment. Photographed on 23 December 1981, during the late stages of excavation and reconstruction, before new landscaping covered the walls of the excavation. Stratigraphy similar to that of Candi Kedulan (Fig. 4, column E_i); additional stratigraphic description of Sambisari byBudianto Toha (1983).

None of these observations or possible explanations confirms the supposed somma-forming collapse of Old Merapi. The best evidence remains the somma itself and the apparent absence of Old Merapi rocks high on the west flank of Merapi.

5.8. Growth of New Merapi

Eruptions of New Merapi began soon after the collapse of Old Merapi. Many tens, perhaps hundreds, of several-millimeter to several centimeter-thick ash and lapilli fall beds, and several-meter-thick valleyfilling pyroclastic-flow deposits, indicate frequent, small- to moderate-sized explosive eruptions through the past millennium. Larger explosive events are indicated by widespread lapilli fall units, a few overbank sheets of pyroclastic-flow deposit and widespread deposits of fine-grained ash that was elutriated from pyroclastic flows and emplaced by ash-cloud surge or fall (Figs. 4 and 7). Many of the pyroclastic-flow deposits that predate the 20th century consist of scoriaceous or pumiceous andesite; most but not all of the 20th century pyroclastic-flow deposits are rich in angular clasts of dense andesite from dome collapse.

Rather than attempt an eruption-by-eruption account of New Merapi, which is better done by Andreastuti et al. (2000 – this volume) (and work in progress), we mention several distinctive types of pyroclastic deposits of New Merapi.

The first is fine-grained, light gray to tan ash that was deposited from both surge and fall events. Accretionary lapilli and vesicle-like voids are common, as are leaf molds. Such layers are found on most interfluves across the entire reach of the pyroclastic apron and even much of the alluvial apron, locally in meter-thick packets of stratified ash and elsewhere in multiple, thinner layers separated by



Fig. 7. Scanning electronic microscope image of fine ash that immediately overlay the floor of Candi Sambisari (Fig. 4, unit E_i -15). Sample was taken from the eastern cutbank of the temple excavation, at the level of the temple floor, shortly after the excavation was completed and before subsequent landscaping. SEM image courtesy of Grant Heiken, Los Alamos National Laboratory. Abbreviations: s, shard; p, phenocryst; mag, magnetite; pl, plagioclase.

thin pyroclastic-flow deposits and (or) incipient soils. Berthommier (1990) and Camus et al. (2000 – this volume) term these deposits the "Sambisari series" and interpret them to be the products of phreatomagmatic eruptions. Based on observations of similar ash elutriated from the 1930, 1984 and 1994 domecollapse pyroclastic flows (Neumann van Padang, 1931, 1933; Boudon et al, 1993; Abdurachman et al., 2000 – this volume), we suggest that much of the fine ash of Merapi's slopes was elutriated out of pyroclastic flows and deposited from either ash-cloud surges and as later or more distal fall. The thickness of elutriated ashfall from the 1930 eruption reached as high as 40 cm on the SE slopes of Merapi (Neumann van Padang, 1931, 1933).

Some examples of this fine, mostly elutriated ash, e.g. H-9 in Sleman and units D-10 and F-21 in Kaliadem and Pelem, are tan-colored, several-meterthick accumulations that contain concentric-structured accretionary balls with diameters up to 6 cm. We originally interpreted these balls to be giant accretionary lapilli, perhaps rolled into place like snowballs. Later, though, we found balls in varying degrees of formation within active ant nests. Apparently, long after emplacement of the ash, ants excavate a spherical hollow and then progressively fill it from the outside in, cementing the ash fill by secretions. If a non-technical term may be excused, we call them giant ant balls.

The same three specific units might be mistaken for tephra fall were it not for sparse lithic lapilli with semi- to fully-consistent paleomagnetic vectors indicative of hot, surge emplacement. A similar example of fine ash, L-1a at Borobudur, is probably too distant to be formed from surges and is instead, we judge, a fall deposit.

Still other examples, e.g. a 40-cm-thick layer that lies at the level of the floor of Candi Sambisari and Candi Kedulan (Fig. 3, location E_i ; Fig. 4, unit E_i -15; Fig. 6, photograph), could be either surge or fall deposit. This unit was sampled at Candi Sambisari in 1981 from just below the water table during a brief window of opportunity between temple excavation and subsequent concrete landscaping. The same unit at nearby Candi Kedulan contains sparse, small bits of charcoal but lacks bedding features that could discriminate between a fall and surge emplacement. Under an SEM, sample E_i-15 from Candi Sambisari appears as mostly equant, poorly vesicular vitric grains with mean diameter of $\sim 25 \,\mu\text{m}$ (Fig. 7). About 2-5% of the grains are equant lithic clasts that could be coeval with the vitric grains or broken from a fresh dome (Heiken, written commun., 1996). Based on the shapes of grains, this unit (the "Deles"(?) ash of Andreastuti et al., 2000 - this volume) could be the product of phreatomagmatic explosions or it could be ash generated by extreme comminution in and elutriation from dome-collapse pyroclastic flows. Ash elutriated from lithic-rich dome-collapse pyroclastic flows is naturally dominated by blocky shapes rather than by glass shards that characterize the "coignimbrite" ash from pumiceous pyroclastic flows.

A second distinctive type of pyroclastic deposit is a fines-depleted, stratified and often cross-bedded, lithic-rich flow deposit on interfluves of the pyroclastic fans. Such deposits can be as thin as a few centimeters or as thick as several meters, roughly blanket topography but thicken locally in topographic lows, and contain abundant charred twigs and logs that are usually aligned in a downslope flow direction. We have termed these deposits "overbank pyroclasticflow deposits" because they are found only on interfluves and, in at least one case, could be traced to a nearby, valley-filling pyroclastic-flow deposit. The "pyroclastic surge facies" of the 1994 pyroclastic flows, described well by Abdurachman et al. (2000 - this volume), is very similar except for less complete charring of wood, and, in the 1994 case, detachment of the surge facies from its parent block-and-ash flow is thought to have occurred as high as the head of the pyroclastic fan (break in slope), not simply along the rim of box canyons. Another example, a deposit containing abundant charred bamboo with $\pm 1\sigma$ calendar equivalence between 1638 and 1806 A.D., is the third pyroclastic-flow unit below the surface at the new Merapi Golf Course (Pagerjurang. Kepuhsari, near the location symbol D in Fig. 3).

A third distinctive pyroclastic deposit—a breadcrust bomb-rich, explosion-type pyroclastic-flow deposit (unit D-1, Fig. 4)—extends over a sizeable part of the interfluve surface between Kali Gendol and Kali Kuning, from near the Kaliadem campground down to (and beyond?) the Merapi Golf Course. It is the youngest major interfluve pyroclastic-flow deposit of the south flank; a sample of charcoal from this has a $\pm 1\sigma$ calendar age equivalence between 1674 and 1817 A.D., but historical records suggest that the flow occurred during the 1822 or 1872 eruption. Older examples undoubtedly exist, but their deposits are not as continuous as those of this historical event.

These three types of pyroclastic deposits, together with tephra falls and valley-filling explosion-type and dome-collapse pyroclastic-flow deposits, comprise the pyroclastic fan deposits of new Merapi.

5.9. Small debris avalanche during growth of New Merapi

A 10-m diameter outcrop of debris-avalanche breccia (G-13) was exposed by erosion after the 1994 pyroclastic flows, on the floor of Kali Boyong at about 970 m elevation and just upslope from Fig. 3, location G. The deposit is of mixed block and matrix facies in the terminology of Glicken (1986) (or "axial B facies" of Palmer et al., 1991) (Fig. 5). Individual lava clasts and lava megaclasts show jigsaw fractures. About 700 m downstream, an apparently correlative 6 m diameter megaclast of pyroclastic deposit is also exposed. The latter apparently cuts and postdates a lithic pyroclastic-flow deposit (G-14) that is $1130 \pm$ 50^{14} C y old, which implies that this debris avalanche cannot be from the somma-forming collapse of $\sim 1900^{-14}$ C y B.P. Regrettably, these two exposures tell us nothing about the volume or reach of the event.

Many collapse-prone stratovolcanoes have collapsed and rebuilt themselves more than once (Siebert et al., 1987; Siebert, 1996), so two or even more such events at Merapi would not be surprising. Following van Bemmelen (1949), we refer to the \sim 1900-year-old, somma-producing collapse as the end of Old Merapi, and envision that the collapse implied by outcrops in Kali Boyong was a relatively small, more recent collapse.

One young packet of fine, leaf-bearing ash (Deles unit, Dls, of Andreastuti et al., 2000 – this volume, including units C-12, D-10, E_i -15, F-19 and F-20, and,

tentatively, Fig. 4, H-9) appears to have been emplaced a little more than 700 14 C y B.P. (~1300 A.D.). Its age allows the possibility, but does not prove, that its eruptions might have been induced by the second, smaller debris avalanche. No direct contact relations between the debris avalanche and the "Deles ash" were found.

5.10. Continued filling, or formation anew, of Lake Borobudur

Three young radiocarbon ages from deposits of Lake Borobudur, ranging in age from 860 ± 95 to 660 ± 110^{-14} C y B.P. (Fig. 4, unit L-2; dates from Murwanto, 1996), indicate either continued or renewed sedimentation in Lake Borobudur. As discussed in connection with Old Merapi, a nearly 3000 year spread in ages in these sediments might indicate: (a) a long-lived lake, lasting from ~ 3430 until $\sim 660^{-14}$ C y B.P.; or (b) two lakes, one formed and filled \sim 3430 ¹⁴C y B.P. and another formed and filled in the same area \sim 860–660 ¹⁴C y B.P. (\sim 1200– 1400 A.D.). The record of deposits is ambiguous. A change from black to yellow deposits indicates that by \sim 660 ¹⁴C v B.P., conditions at the bottom of the lake were more oxidizing than previously, but we cannot attribute the black sediment to an early lake and the yellow sediment to a younger lake, because two of the young ages (860 \pm 95 and 680 \pm 95 14 C y) were also from black claystone.

The possibility that a (2nd generation?) Lake Borobudur existed before, during, and (or) soon after construction of Candi Borobudur is information that will surely interest archaeologists.

5.11. Colonial and postcolonial eruptions

At least six moderately large explosive eruptions have occurred in colonial and postcolonial time, in 1587, 1672, 1768, 1822, 1849 and 1872 (Hartmann, 1935; Zen et al., 1980; Berthommier and Camus, 1991). In 1822, tephra fell both northeast and northwest of the volcano and pyroclastic flows traveled down the Apu, Lamat, Blongkeng, Batang, Gendol and Woro River valleys (Berthommier, 1990). The most recent large explosion-type flows, in 1822 and (or) 1872, reached "far" (10–15 km?) down the Blongkeng, Senowo, Trising, Apu, Gendol and Woro River valleys, and, perhaps, across the interfluve upon which the government-approved Merapi Golf course was built in Pagerjurang, Kepuhsari, 10 km from the summit (Fig. 4, unit D-1). At least two pyroclastic-flow deposits below this one at the golf course also occurred within colonial time. The most recent small explosion-type pyroclastic flow at Merapi occurred in 1969 (Suryo, 1978; and field work by the authors).

High on the cone of New Merapi, some lava flows have been identified with specific historical eruptions (for examples, see Camus et al., 2000 – this volume); others are of unknown but geologically recent age. Most lava that flows onto the steep upper parts of the cone collapses. A large lava-dome collapse, possibly but not definitely including an explosive component, occurred in 1930 (Newmann van Padang, 1931, 1933; Kemmerling, 1932; Escher, 1933). The largest pyroclastic flow of this event reached 13.5 km from the summit. Most other 20th century eruptions, typified by dome-collapse events of 1984, 1992 and 1994, have been smaller and less explosive, and resulting pyroclastic flows have reached <8 km from the vent. Interested readers can consult Hartmann (1935), Kusumadinata (1979), Suryo and Clarke (1985) and Berthommier and Camus (1991) for more details of the colonial and postcolonial record.

6. Relation of volcanism to 8–10th century A.D. temples

"Slip-failure" and a catastrophic eruption of Merapi Volcano, supposedly in 1006 A.D., are reputed to have forced the demise or eastward migration of the Mataram civilization of Central Java (IJzerman, 1891; Scheltema, 1912; van Hinloopen Labberton, 1922; van Bemmelen, 1949, 1956, 1971). However, the idea that the Mataram civilization moved to East Java in response to an eruption of Merapi in 1006 A.D. "is certainly wrong, because the palace had already been shifted to the Brantas delta (East Java) at that time" (Boechari, 1976). Could earlier eruptions of Merapi caused an earlier shift to East Java?

6.1. Archaeological information

What is known of the Mataram civilization, and especially the chronology of its temples, that might yield clues to any volcanic influence on the society? Stone inscriptions on the numerous temples of central Java indicate a thriving Hindu and Buddhist civilization from at least 732 until 928 A.D. (Miksic, 1990). Major temples were constructed until about 856 A.D. (Provincial Government of Central Java, 1982; Dumarçay, 1978, 1986); smaller but still impressive temples, e.g. C. Plaosan, C. Sari, C. Awu and C. Lumbung, were constructed through the latter half of the 9th century (Sarkar, 1971/72; Dumarçay, 1986).

At Borobudur, initial construction of a central plateau and a massive stone structure between 760 and 770 A.D. was of Hindu or Javanese design for an unknown purpose (Dumarçay, 1986; Miksic, 1990). Was the change to a Buddhist theme in ca. 780 A.D. a response to a change of political power from Hindu Sanjaya dynasty of north-central Java to the Buddhist Sailendra family of the south? Or might the architectural and (or) political changes have resulted from eruptions of Merapi that re-formed and refilled Lake Borobudur?

Similarly, a stone inscription issued by a Sailendra king and found at Candi Plaosan, nearer to Merapi, suggested to de Casparis (1956, p. 205) that new temple construction began over an older foundation, after some decay of the original temple. Might this decay represent an impact of a volcanic eruption?

Power was held by the Buddhist Sailendra family from 780 until 832 A.D., and then shared in an uneasy intermarriage relation between the Sailendra and Sanjaya families until 850 A.D., when the Sanjaya family regained exclusive control (Miksic, 1990). From 832 until 850 A.D., temples that were under construction (including Borobudur) were completed with only slight changes in style. Subsequently, construction of Candi Prambanan and Candi Sambisari (lasting to 856 A.D. at Prambanan) was nearly all of Hindu origin. By the end of the 9th century, though, some events or circumstances (without change of dynasty) brought temple building in the Merapi region to a complete halt. Temples that were under construction were completed in basic form, though some sculptures were unfinished; no new construction began. Was the regional building trend stopped by exhaustion of money, people and (or) building materials? By functional completion? Or did Merapi eruptive activity intervene?

Before 928 A.D., more than 100 stone and copper

inscriptions in Sanskrit and Old Javanese provide details of local kings, taxes and property transfers (de Casparis, 1950, 1956, 1988; Sarkar, 1971/72). Volcanic eruptions seem to have been a normal part of Javanese cosmology. One stone inscription, for example, carved in 824 A.D. and found northwest of Gunung Merapi, prays that a king might ascend in Buddhist merit "so long as the underground fire breathing hot remains, as the wise see, unsuppressed through the openings which are in its control, so long as the earth remains also, and the Meru inhabited by the gods remains, also, so long as Vrtra (Sun) of the sky scatters his own rays..." (Sarkar, 1971).

Spirits of Merapi and several other volcanoes were invoked in prayers of the time, as additions to standard Buddhist and Hindu prayers. According to Sarkar (1971, p. xxiii)", behind the charming Hindu and Buddhist facade, there remained the spirit-world of Indonesian conception and it was a very real one. Indeed, the spirits of the mountain ranges, as invoked in some inscriptions seem to refer to the hovering spirits of the ancestors, who arrive in villages like demi-gods, rushing through the ways of the firmament. These spirits of the ancestors have always elicited the awe and respect of the Javanese people. Perhaps this spirit-world constitutes the matrixwhich was never perhaps fundamentally shaken by Indian religious concepts-upon which the Indian religious systems were superimposed". [Note: even today, some residents believe that eruptions are the consummation of marriage between the god of the mountain, Kyai Sapujagad, and the goddess of the south sea, Nyai Rara Kidul. Ritual offerings and prayers ask Nyai Rara Kidul to spare villages when she summons forth the lava (Laksono, 1988).

In contrast, for the period from 928 A.D. until the 15th century, only one inscription has been found in Central Java (Fontein, 1990). Apparently, the new king Sindok moved the kraton (seat of government) to East Java, where he ruled until 947 A.D. (de Casparis, 1988). The reasons for this shift to East Java have puzzled archaeologists and historians for many decades (Dumarçay, 1986; Miksic, 1990).

Curiously, from archaeological sites around Merapi, we know that some people remained in central Java past 928 A.D., but that they reverted from a centralized government (capable of building temples) to local government (de Casparis, 1950; Dumarçay, 1986). Pot sherds of 10th and 11th century styles have been found in archaeological sites surrounding Central Javanese temples, indicating that these sites were occupied more or less continuously through this period. Dumarçay (1986) also concluded that Candi Sambisari remained unburied until after the 14th or 15th century because the site was pillaged by Islamic invaders who did not arrive in Central Java until that time.

6.2. Stratigraphic information

What new information about Merapi's eruptions might shed light on mysteries of the temples? Deposits and radiocarbon data (Fig. 4, Table 1) indicate that explosive eruptions of widespread impact occurred before, during and after the period of temple construction (Table 1). During each explosive eruption, people within the range of pyroclastic flows and surges would have been killed, and ashfall could, at least in one downwind sector per eruption, have caused crops to fail for a year or more. The surviving workforce could have been distracted, if not hungry. After each large explosive eruption, lahars and overbank floods would have caused more damage.

About 10 km northwest of the summit (Fig. 4, column M), at least three small temples were partly covered by deposits from New Merapi. Candi Lumbung (*lumbung* = "place for pounding rice") is covered by 6–7 m of tephra, pyroclastic-flow and coarse lahar deposit. Two ¹⁴C ages indicate burial beginning after ~650 A.D. and the upper half or more of burial occurring after ~1500 A.D. Nearby, a bomb-rich, 3 m-thick, explosion-type pyroclastic-flow deposit (unit M-14; 980 ± 80 ¹⁴C y, 1 σ calendar equivalence between 994 and 1186 A.D.) is the second unit *above* the floor of Candi Pendem ("buried temple"). An eruption around ~1000 A.D. would have been 1–2 centuries after its completion.

About 16 km south–southeast of Merapi, Candi Morangan was badly damaged and buried at an unknown date by bouldery lahars. Roughly 7 km farther to the south, burial of Candi Sambisari and Candi Kedulan began about 4 centuries after they were built (\sim 740 ± 50 ¹⁴C y (\sim 1261–1295 A.D.), age of the first ash deposit that lies on the floor of Candi Kedulan). Either no eruptions of the preceding 4 centuries affected those temples, or, more likely,

those who were occupying the temple sites kept those sites clean until the 13th century. Our result that only the lower 2.5 m of Candi Kedulan was buried in the succeeding \sim 400 years indicates that the upper parts of these temples were still exposed to plunder by Islamic invaders, as Dumarçay surmised. Although the earliest burial of Candi Sambisari and Candi Kedulan was by fine ashfall or ash-cloud surge, by far the dominant burial agents at those temples have been lahars and floodplain deposition, spread over many centuries.

West of Merapi, indications of ash thickness at Candi Borobudur are ambiguous. Reports from early expeditions to explore and restore Borobudur spoke of thick volcanic debris, but some of this could have been soil from the victorious jungle. Only 1 km to the west, ash of unit L-1 is >2 m thick, and some or even all of this could postdate construction of Borobudur, but we do not have age control for this specific outcrop. At the other extreme, Moendardjito (1982) and Nossin and Voûte (1986a,b) suggest that only a few centimeters of ash covered Borobudur temple.

Nearby and topographically a few meters lower than L-1, Lake Borobudur either still existed or reformed by the 12-13th century A.D. It could have surrounded the temple, which was built on a hill that rose ~ 15 m above the surroundings (Sampurno, 1969). This lake would have filled with water within just a few years, and then with sediment by $\sim 660^{-14}$ C y B.P. (13–14th century A.D.). Thanikaimoni (1983), a palynologist, examined soils excavated from C. Borobudur and found no evidence of a nearby marshy lake during or since its construction, but the lake sediments and the wood fragments that they contain prove that a lake was, in fact, present. The fact that marshy water pollen are absent in sandy, andesite clast-rich soil that was used in C. Borobudur's foundation (Sampurno, 1969) might indicate that the new Lake Borobudur did not form until after construction; alternatively, it might indicate that those who built the temple used good geotechnical judgement and avoided the black clayey lake sediments from the earlier Lake Borobudur.

Candi Mendut, closer to Merapi than Borobudur, was once buried by ~ 3 m of stratified floodplain and lahar deposit, separated by thin ash-fall layers (Scheltema, 1912, p. 225; Nossin and Voûte, 1986a,b). In sum, there is stratigraphic evidence that Merapi eruptions have affected temples of the area, out to radii of 20 and even 30 km, though not necessarily during a single large eruption. Merapi's eruptions certainly stressed and may have caused decline of the Mataram civilization of Central Java. Events at Merapi certainly could have caused Sindok to move the kraton to East Java, though not at the late, 1006 A.D. date suggested by van Hinloopen Labberton and van Bemmelen.

7. Modern hazards implications

Most eruptions during the 20th century have produced viscous lava domes that collapsed to form pyroclastic flows of limited volume and reach. Occasionally, as in 1930, unusually large collapse-related flows reached >10 km from the summit and into populated areas (Kemmerling, 1931; Neumann van Padang, 1931, 1933, 1936/1937; Escher, 1933; Hartmann, 1934, 1935).

However, many eruptions during the 7-19th centuries A.D. were substantially more violent and swept broad sectors of the volcano with explosiontype pyroclastic flows. These eruptions, much larger and more explosive than any of the 20th century, have occurred on average about once per century. Widespread pyroclastic flows and surges traveled at least 15 km and perhaps even 20-25 km down the southwest and probably other flanks of Merapi. Clearly, Merapi produces not only dome-collapse pyroclastic flows, but also pyroclastic flows from moderate to large explosive eruptions. The relatively small "Merapi-type", dome-collapse pyroclastic flows that have dominated recent activity are not the exclusive, or even the typical, behavior of Merapi; larger but less frequent explosive eruptions are also typical of Merapi.

Knowledge of the large explosive eruptions in Merapi's history poses two challenges for volcanologists. The first is to judge whether relatively small eruptions of the 20th century are: (a) a new style of open-vent, frequent and thus less hazardous eruption that will continue for the foreseeable future ("newly open vent" or "newly reduced hazards scenario"); or (b) a "background" level of activity that can be interrupted upon relatively short notice by much larger explosive eruptions ("interruptable background scenario").

Merapi's long record of explosive eruptions, within which less-explosive dome growth and dome collapse has certainly occurred, suggests that (b) is more likely. We find no reliable evidence—indeed, no reason to think—that future activity will be as benign as that of the 20th century.

The second and more difficult challenge, particularly acute for the "interruptable background" scenario, is to provide timely warning of one of these larger explosive eruptions that could devastate areas far beyond present hazard zones. Are any features in either the stratigraphic or petrologic record, or volcano monitoring data, likely to foretell of a much larger eruption? At Merapi, no distinctive precursor of large explosive events has yet been recognized. Elsewhere, some large explosive eruptions have shown distinctive precursors, but others seem only to have modest precursors that do not indicate the magnitude of the impending eruption (Newhall and Dzurisin, 1988, p. 26). And, even if unique precursors are recognized, how can their reliability be established, and, given the real possibility of a false alarm, how will volcanologists convince officials that hundreds of thousands of people who are accustomed to small eruptions must move to be safe?

Many villages and towns around Merapi are built on deposits of these larger explosive eruptions. At least 80,000 and perhaps as many as 100,000 people live inside the so-called Forbidden Zone (an area of roughly 10 km radius, mainly on the west and south sides of the volcano, defined by Pardyanto et al, 1978) (population figures from Lavigne, written commun., 1995 and Siswowidjoyo, oral commun., 1995). Several hundred thousand more live just a few kilometers outside that zone. All of these residents are familiar with small dome-collapse awan panas guguran, such as that which killed ~ 75 people in Desa Turgo in 1994. But how many realize that their homes and schools are built on deposits of much larger, relatively young, lethal explosive eruptions?

Evacuations during recent eruptions have been kept small by political and scientific decisions to minimize "unnecessary" disruption of the lives of those who live on Merapi's slopes. During any one eruption, only certain sectors of the Forbidden Zone have been evacuated. Fertile land in central Java is scarce because of the dense population, and those who have land on Merapi's slopes have deep community and economic attachments to that land. However, the geologic record shows clearly that danger from larger explosive eruptions can cover not only the whole of the Forbidden Zone but also areas extending many kilometers beyond that zone.

We can give no assurance from the geologic record that Merapi will remain as quiet in the next century as it has during the 20th century. Rather, we suspect that the quiet of the 20th century will be broken by a larger explosive eruption within coming decades. Large numbers of people, both within and beyond the Forbidden Zone will be at serious risk. Candid public education and discussion of the intent of the Forbidden Zone, a willingness among all parties to accept some false alarms, and an ongoing search for precursors of a larger explosive eruptions of Merapi and similar volcanoes are all needed to limit and reduce that otherwise-growing risk.

8. Conclusions

Our reconnaissance study of the pyroclastic stratigraphy of Merapi suggests revisions to previous accounts of Merapi's evolution. Old Merapi grew by lava extrusion and explosive eruptions from at least 8600 B.C. until ~ 100 A.D., when it collapsed in a debris avalanche.

Eruptions of New Merapi followed, producing lavas, tephra fall and pyroclastic flows. The last traveled mainly to the west and south. Later explosive eruptions no doubt removed some material from the growing cone, and there was apparently one smaller edifice collapse and debris avalanche sometime between 800 and 1300 A.D., but for most of the current millennium, rates of growth have outpaced destruction to build the modern cone.

Explosive eruptions occurred before, during and after construction of the major temples of Central Java. We cannot prove that eruptions caused the decentralization of civilization in Central Java, but we can say that these early eruptions would have been very disruptive, and crops might easily have failed. A lake also formed around Candi Borobudur, though the precise timing of the lake relative to construction and abandonment of Candi Borobudur is uncertain.

Merapi's long history of large explosive eruptions eruptions larger than any in the 20th century—suggests a need to reconsider existing hazard maps, monitoring strategy, and emergency plans. Eruptions like many of the past could sweep through and beyond the current Forbidden Zone and even through the first danger zone, and there is no reliable method, at present, to anticipate whether or when Merapi will interrupt its relatively benign activity of the 20th century with a larger explosive event.

Acknowledgements

The studies reported in this paper began in 1981 as part of US Geological Survey (USGS) Volcanological Survey of Indonesia (VSI) collaboration for upgrading the surveillance of Merapi Volcano. It was a mixed blessing to spread the work over so many years and so many workers: continuity and correlations suffered, but new outcrops and data were added. We thank all colleagues who took part in those projects. Profs Boechari and Dumarçay generously shared their knowledge of temples and early history of this region. Prof Pierre Vincent kindly provided copies of work by his student, Pascale Berthommier, and reviews of the present paper by Vincent, G. Camus, W.E. Scott, Game McGimsey, and Barry Voight are thankfully acknowledged. The K-Ar age was provided by Marvin Lanphere (USGS, Menlo Park), Grant Heiken offered the SEM image and a second opinion the origin of ash bed E_i-15, and Shannon Hayes helped with revisions of the stratigraphic columns.

Primary financial support was provided by the USGS and VSI, and by the US Agency for International Development (USAID) and the Asian Development Bank (Loan 641-IND). The work of M.A.M. was supported by grants from Sigma Xi, the Geological Society of America, and NASA (Grant NAG-5-32).

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