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

C.G. Newhall[a,*], S. Bronto[b], B. Alloway[c,1], N.G. Banks[a], I. Bahar[b], M.A. del Marmol[d], R.D. Hadisantono[b], R.T. Holcomb[a], J. McGeehin[a], J.N. Miksic[2,e], M. Rubin[a], S.D. Sayudi[b], R. Sukhyar[b], S. Andreastuti[b], R.I. Tilling[a], R. Torley[a,f], D. Trimble[a], A.D. Wirakusumah[b]

[a]*US Geological Survey, Department of Geological Sciences, Box 351310, University of Washington, Seattle, WA 98195, USA*
[b]*Volcanological Survey of Indonesia, Jl. Diponegoro 57, Bandung, West Java, Indonesia*
[c]*University of Auckland, Tamaki Campus, Private Bag 92019, Auckland, New Zealand*
[d]*Department of Earth and Planetary Sciences, The Johns Hopkins University, Baltimore, MD 21218, USA*
[e]*Gadjah Mada University, Yogyakarta, Indonesia*
[f]*Department of Geological Sciences, University of Oregon, Eugene, OR 97403, USA*

Abstract

Stratigraphy and radiocarbon dating of pyroclastic deposits at Merapi Volcano, Central Java, reveals ~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 ~3400 ^{14}C y B.P. hints at a possible early collapse of Merapi. The latest somma-forming collapse occurred ~1900 ^{14}C 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 ~900 A.D. (roughly, 1400–1000 ^{14}C 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 ± 50 ^{14}C y B.P. Eruptions ~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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* Corresponding author. Fax: +206-543-3836.
E-mail address: cnewhall@usgs.gov (C.G. Newhall).

[1] Present address: Institute of Geological & Nuclear Sciences, Wairakei Research Centre, Private Bag 2000, Taupo, New Zealand.

[2] Present address: National University of Singapore, Singapore.

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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.

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 ash-cloud 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.

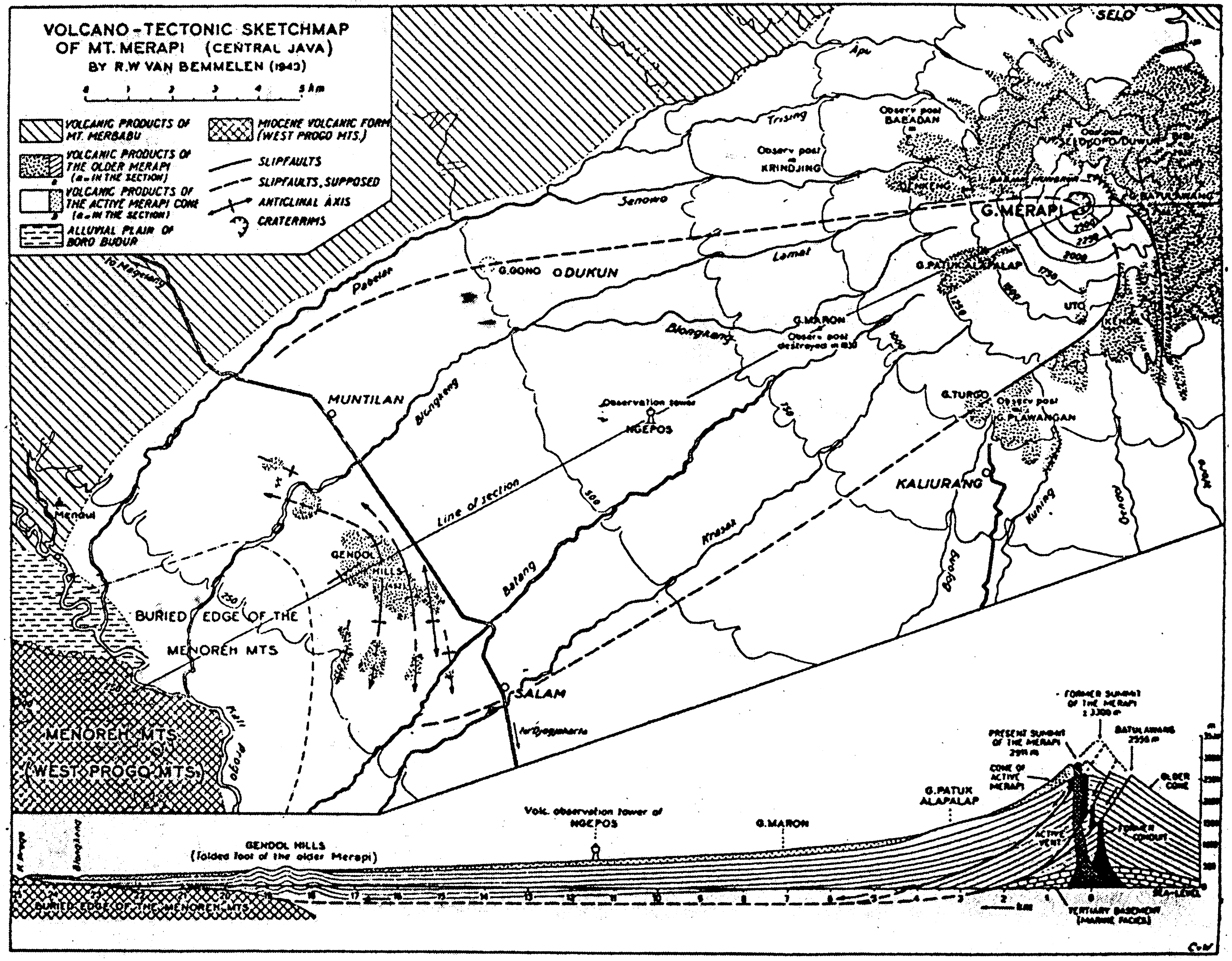


Fig. 2. Geology of Merapi as inferred by van Bemmelen (1949). Elevations in meters.

(3) Ages are expressed in calibrated calendar years where pertinent to archaeological discussions, and in ^{14}C 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 (~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 small-volume 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 dome-collapse 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 ^{14}C years	Calibrated ages and (1σ range) calibrated[a]	Deposit, dated material[b], location, sector
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 (correlates with W-5378)	MN-50ee	360 ± 100	~1550 (1441–1654)	p flow, Kinaredjo-Pelem, S
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 (correlates with W-5373)	MN-50w	1015 ± 100	1020 (899–1161)	ash cloud surge, Kinaredjo-Pelem, S
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*)

Section and unit	Lab no.	Field no.	Age, B.P ^{14}C years	Calibrated ages and (1σ 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 with W-5421)				
F-22	W-5421	MN-50t	1700 ± 120	380 (229–532)	ash cloud surge, Pelem, S
End of known basaltic products (del Marmol, 1989)					
F-28	W-5370	MN-49f	1840 ± 150	220 (19–390)	p flow, Kinaredjo, S
Somma rim, earliest possible IF no pyroclastic flows could travel east after 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-30o	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 (~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 ^{14}C 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 correlations—both 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;

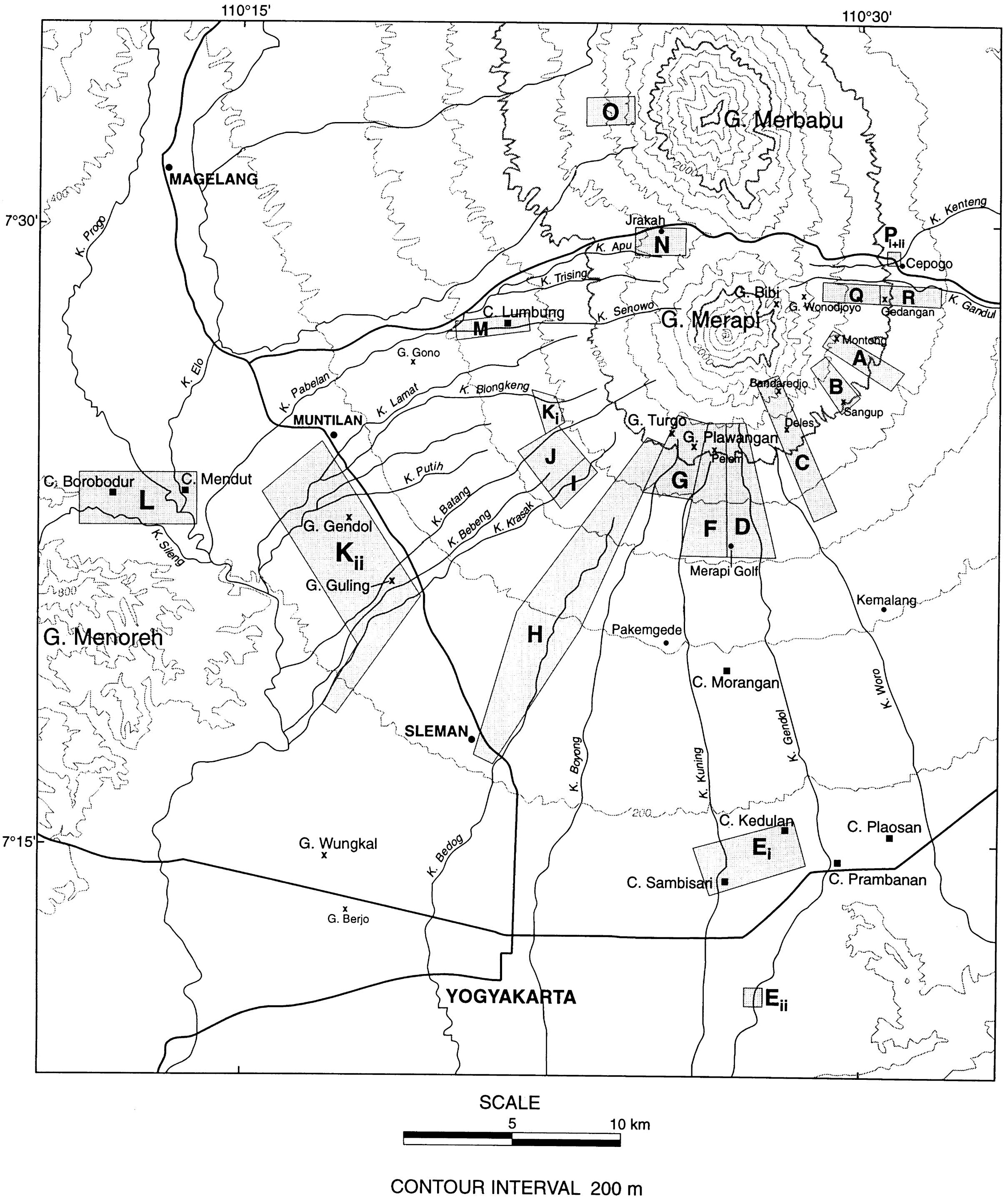
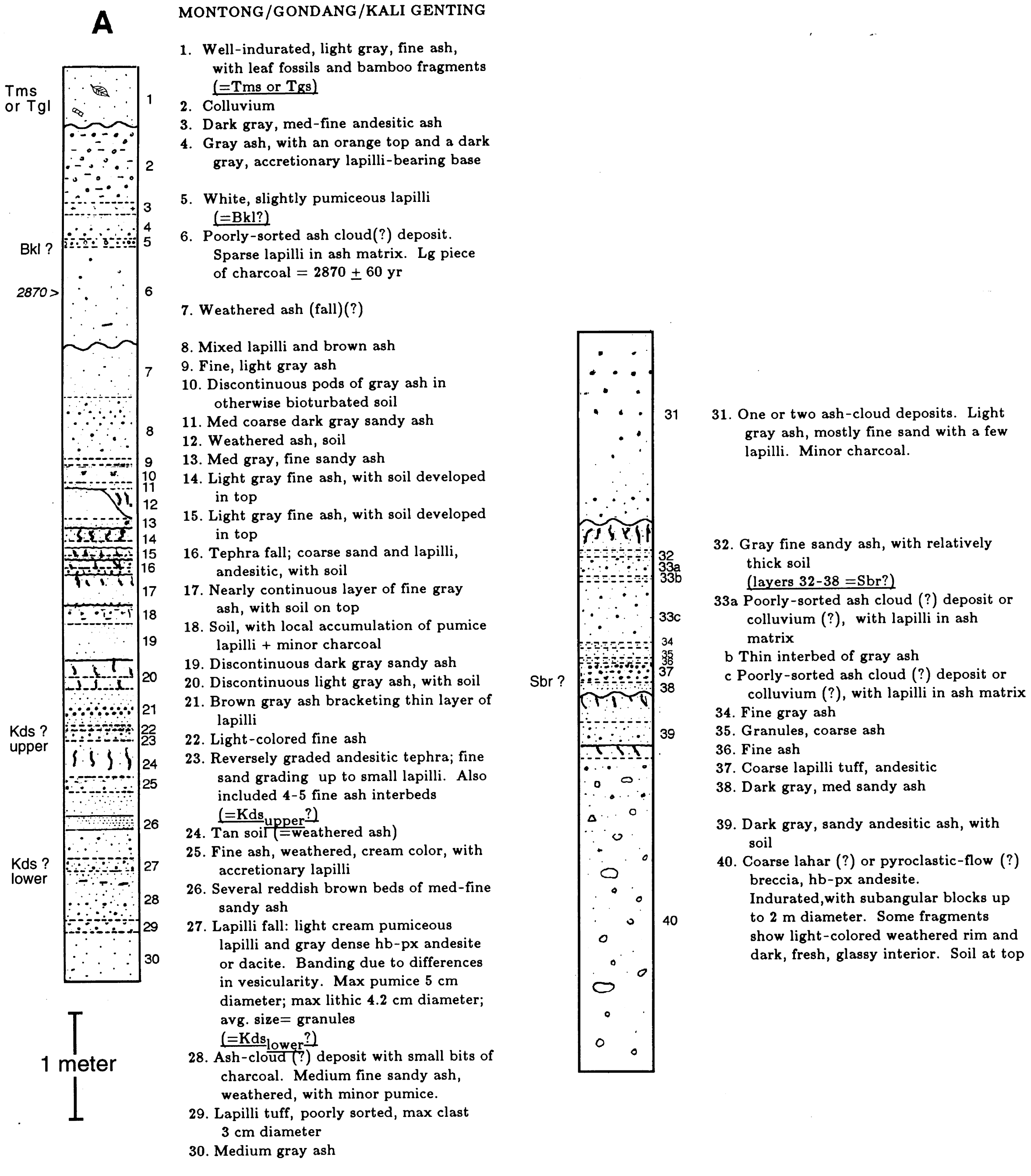


Fig. 3. Locations of composite stratigraphic sections and other places cited in text.



MONTONG/GONDANG/KALI GENTING

1. Well-indurated, light gray, fine ash, with leaf fossils and bamboo fragments (=Tms or Tgs)
2. Colluvium
3. Dark gray, med-fine andesitic ash
4. Gray ash, with an orange top and a dark gray, accretionary lapilli-bearing base
5. White, slightly pumiceous lapilli (=Bkl?)
6. Poorly-sorted ash cloud(?) deposit. Sparse lapilli in ash matrix. Lg piece of charcoal = 2870 ± 60 yr
7. Weathered ash (fall)(?)
8. Mixed lapilli and brown ash
9. Fine, light gray ash
10. Discontinuous pods of gray ash in otherwise bioturbated soil
11. Med coarse dark gray sandy ash
12. Weathered ash, soil
13. Med gray, fine sandy ash
14. Light gray fine ash, with soil developed in top
15. Light gray fine ash, with soil developed in top
16. Tephra fall; coarse sand and lapilli, andesitic, with soil
17. Nearly continuous layer of fine gray ash, with soil on top
18. Soil, with local accumulation of pumice lapilli + minor charcoal
19. Discontinuous dark gray sandy ash
20. Discontinuous light gray ash, with soil
21. Brown gray ash bracketing thin layer of lapilli
22. Light-colored fine ash
23. Reversely graded andesitic tephra; fine sand grading up to small lapilli. Also included 4-5 fine ash interbeds ($=\mathrm{Kds}_{\mathrm{upper}}$?)
24. Tan soil (=weathered ash)
25. Fine ash, weathered, cream color, with accretionary lapilli
26. Several reddish brown beds of med-fine sandy ash
27. Lapilli fall: light cream pumiceous lapilli and gray dense hb-px andesite or dacite. Banding due to differences in vesicularity. Max pumice 5 cm diameter; max lithic 4.2 cm diameter; avg. size= granules ($=\mathrm{Kds}_{\mathrm{lower}}$?)
28. Ash-cloud (?) deposit with small bits of charcoal. Medium fine sandy ash, weathered, with minor pumice.
29. Lapilli tuff, poorly sorted, max clast 3 cm diameter
30. Medium gray ash
31. One or two ash-cloud deposits. Light gray ash, mostly fine sand with a few lapilli. Minor charcoal.
32. Gray fine sandy ash, with relatively thick soil (layers 32-38 =Sbr?)

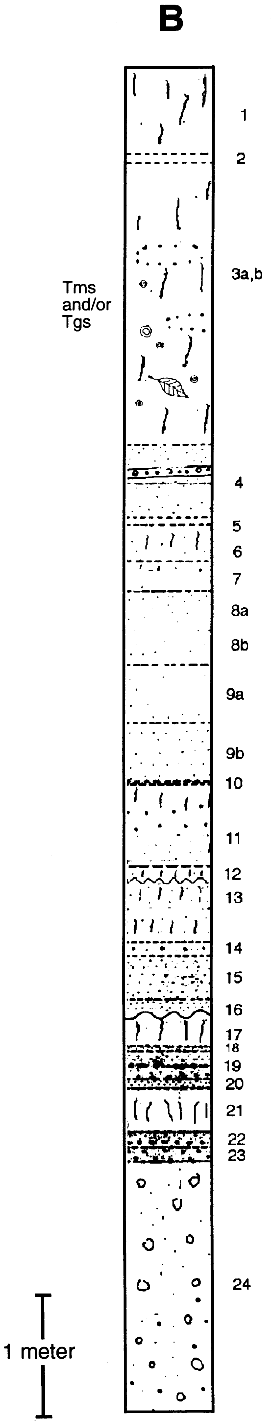
33a Poorly-sorted ash cloud (?) deposit or colluvium (?), with lapilli in ash matrix

b Thin interbed of gray ash

c Poorly-sorted ash cloud (?) deposit or colluvium (?), with lapilli in ash matrix

34. Fine gray ash
35. Granules, coarse ash
36. Fine ash
37. Coarse lapilli tuff, andesitic
38. Dark gray, med sandy ash
39. Dark gray, sandy andesitic ash, with soil
40. Coarse lahar (?) or pyroclastic-flow (?) breccia, hb-px andesite. Indurated, with subangular blocks up to 2 m diameter. Some fragments show light-colored weathered rim and dark, fresh, glassy interior. Soil at top

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).



SANGUP/NGELO

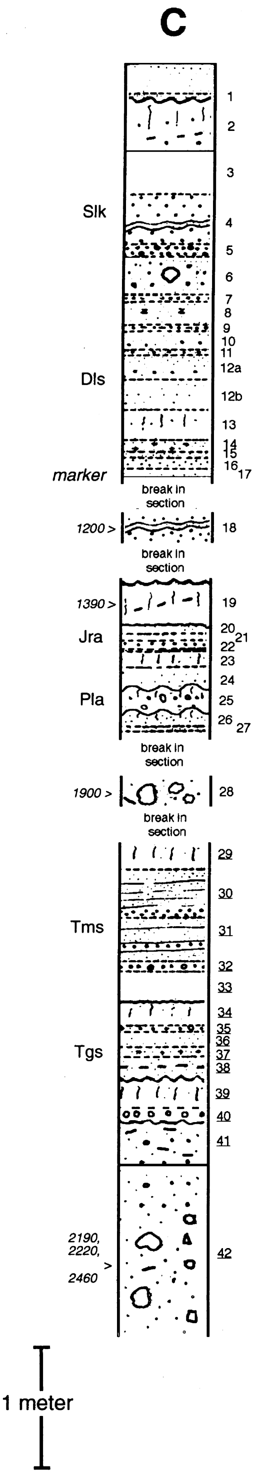
1. Brown soil
2. Gray sandy ash
3. Brown soil; locally within it, tan-brown ash-rich soil, overlying indurated gray ash with accretionary lapilli, leaf fossils. May = Tms or Tgs. Nearby, same horizon, dk gray ash w/ one 10-cm block of dark, px andesite pumice). Discontinuous because bioturbated.
4. Gray ash, with one horizon of cream-colored 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

8a. Fine tan ash
b. Fine light gray ash, grades into overlying unit

9a. Fine tan ash
b. Fine light gray ash, grades into overlying unit

10. Discontinuous gray fine ash
11. Brown lapilli and ash, soil top
12. Brown soil
13. Discontinuous pods of tan-gray ash in brown soil
14. Rusty-brown colored lapilli-fall, moderately dense
15. Gray med sandy ash
16. Dark-gray sandy ash
17. Brown ash-rich soil
18. Gray sandy ash
19. Brown soil with a few pumiceous, cream-colored lapilli
20. Dark gray coarse sandy ash
21. Brown soil
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. Rust-colored.
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. Gray 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, ash-cloud 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

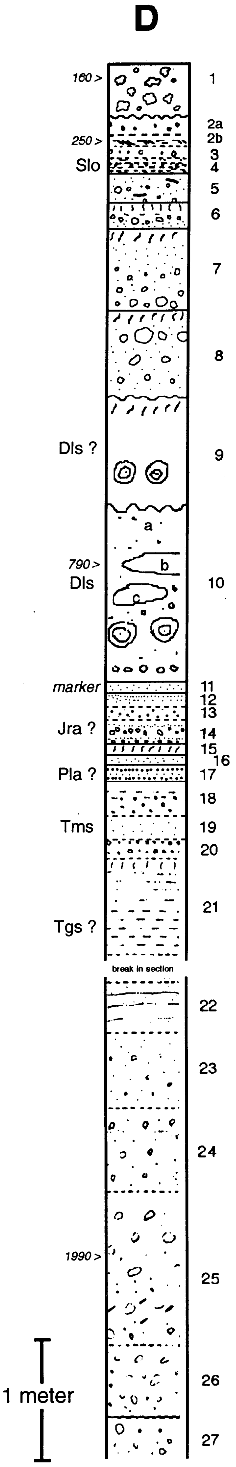
28. Note: On the surface at Dusun Blorong, Desa Siturejo, Kec Kemalang, but at an uncertain stratigraphic position, perhaps near here, there is a breadcrust-bomb-rich pyroclastic-flow deposit, w/ abundant charred logs. 1900 ±50 y (sample MN-420)

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 ± 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

1. Pyroclastic-flow deposit at campground; bomb-rich, age=160±30 y. Might correlate with youngest pyroclastic flow (#6, Bronto and Sayudi, 1995) 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±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)

5. Dark brown, massive pyroclastic-flow deposit, sand and lapilli, charcoal (= Pyro. flow 4 of Bronto and Sayudi, 1995)

6. Pyroclastic-flow deposit (#3 of Bronto and Sayudi, 1995), reverse graded, with charcoal, weathered top

7. Pyroclastic-flow deposit (#2 of Bronto and Sayudi, 1995), normally graded, blocky hb andesite lithics in base; pumiceous lapilli in center, grading up to dk brown silty-sandy ash, w/ charcoal.

8. Pyroclastic-flow deposit (#1 of Bronto and Sayudi, 1995), similar to layer 7

9. Tan, stratified ash with giant ant-cemented 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. (= Dls) 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 (regional marker of Andreastuti et al, this vol.)

12. Gray-brown sandy ash, crudely stratified

13. Gray coarse sand and granules

14. Andesitic lapilli fall deposit (= Jra?)

15. Brown, fine-grained ashy soil

16. Gray ash, with scattered px and/or hb xls

17. Granular, andesitic ash, with scattered cream-colored pumice lapilli. Lenses out. (= Pla?)

18. Pinkish-gray clay with small cream-colored 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?)

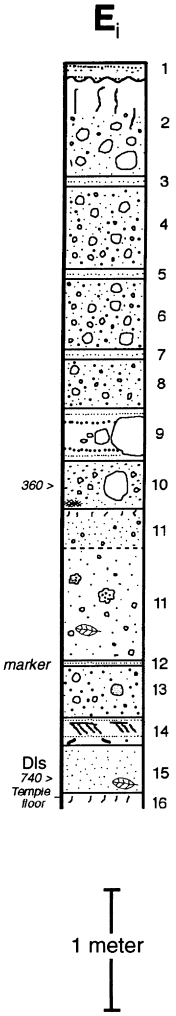
24. Pumiceous pyroclastic-flow deposit (no banded pumice?)

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*)



CANDI KEDULAN, CANDI SAMBISARI

1. Fresh, thinly-bedded sandy sediment**
2. 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
8. Lahar at C. Kedulan, 0.4 m thick; fresh gray pebbly sand at C. Sambisari.
9. Stratified, coarse fluvial sand, with lenses of boulders to 0.5 m dia., 0.1-1.0 m thick. May have two layers.
10. 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.

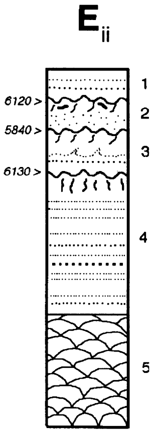
11a. Sandy-silty lahar deposit, massive, 0.4 m thick; well-indurated; soil development at top. Overall color of this+underlying layer = brown-gray.

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 Andreastuti et al, this vol.?)
13. Sandy, granular lahar(?) deposit, with scattered hb-plag pumice; poorly-sorted, 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)
16. 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.

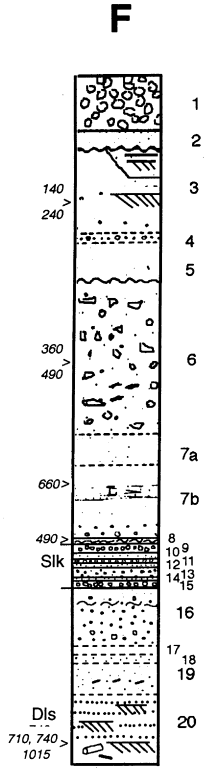
** At C. Sambisari only



WATUADEG

1. Fluvial deposits
2. Finely laminated ash-rich sediment; age=6120±110 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)

Fig. 4. (*continued*)



PELEM/KINAREDJO, KALI KUNING

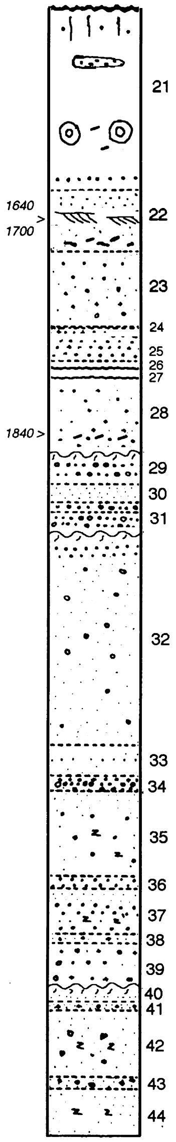
1. Clast-supported, fines-depleted pyroclastic-flow deposit, with both valley-filling and interfluve facies. Age="modern"
2. Very fine light gray ash over sandy gray ash
3. Matrix-supported interfluve pyroclastic flow deposit(s)(2?), cross- and planar-bedding. Ages 140±30; 240±80 y
4. Yellow pumice lapilli, to 4 cm diameter
5. Pinkish-brown, fine-grained ash-cloud deposit
6. Dome-collapse pyroclastic-flow deposit, clast-supported, fines-depleted. 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 pyroclastic-flow 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)



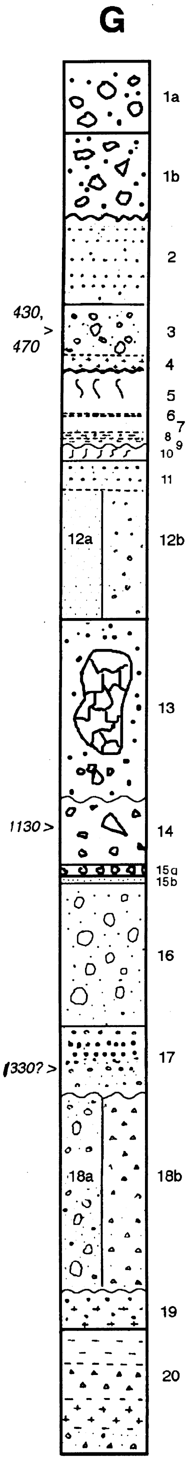
[major color change--brown to gray above]

21. Tan surge, facies of an interfluve pyroclastic flow? Includes lenses of lapilli. Rootless fumaroles and traces of charcoal at top and bottom of layer; 6-cm-dia ant balls.
22. Interfluve pyroclastic-flow deposit. gray sandy ash and lapilli, fines-depleted, some cross-bedding; matrix supported, lots of charcoal. Age 1700±120; 1640±120 yr
23. Brown, vesicular andesitic lapilli, granules
24. Fine ash
25. Brown lapilli, vesicular andesite
26. Very fine, powdery, light-colored ash
27. Gray medium sand ash, crystal-lithic, plag-rich; incipient soil at top
28. Pyroclastic-flow deposit, crystal-rich andesite, matrix supported. Hb & px andesite, lapilli to 5 cm. Abundant charcoal. Age=1840±150
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

[units 29-31 are from a single eruption]

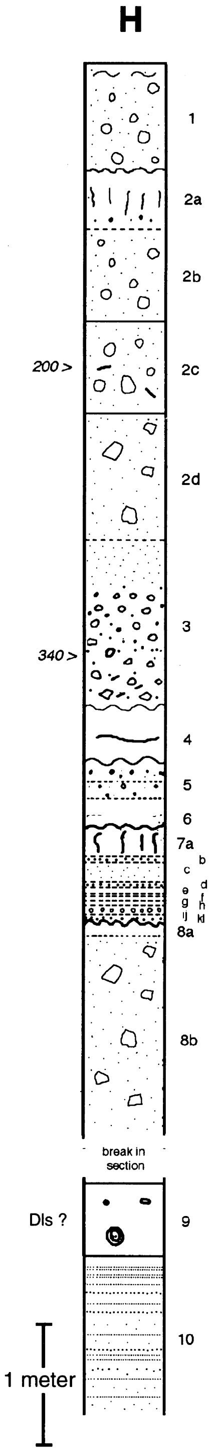
32. Brown ash and lapilli, possibly with a rip-up of F-34; probably a weathered pyroclastic-flow deposit. May have limited exposures of tephra fall at its top
33. Gray, coarse sandy ash, lens, poorly indurated. [possibly young cut and fill?]
34. Yellow-tan pumice and lithic lapilli, px andesite, both densities 2-3 cm diameter
35. Yellow-brown ash with scattered lapilli and granules. Possible weathered pyroclastic-flow deposit.
36. Lapilli
37. Brown ash and lapilli=weathered pyroclastic-flow deposit?
38. Gray lithic granular ash, andesitic
39. Hb andesite(?) pumice, creamy yellow color, max pumice 4 cm; max lithic 3 cm diameter. Grades up into 38.
40. Fine, pinkish gray ash (with soil)
41. Coarse sandy ash, andesitic
42. Brown ash, weathered, pyroclastic-flow deposit (?)
43. Discontinuous layer of hb pumice lapilli
44. Brown weathered ash (interfluve pyroclastic-flow deposit?)

Fig. 4. (*continued*)



KALI BOYONG/PLAWANGAN

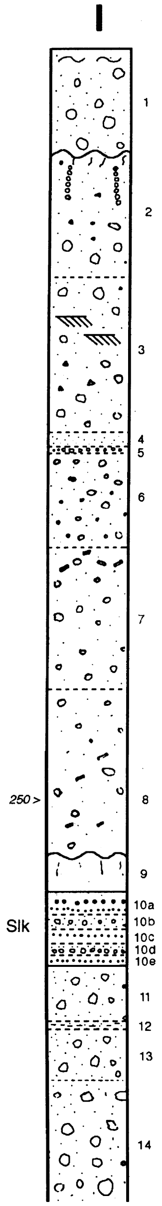
1a. 1994-95 lahar deposits
1b. 1994 pyroclastic-flow deposit in Kali Boyong, with large angular lithic blocks, some breadcrusted. Ash cloud surge in Kaliurang town.
2. Fresh andesitic ash and lapilli fall
3. At least 6 pyroclastic-flow and at least 2 lahar deposits (not to scale). Pyroxene andesite and basaltic andesite; one block with >3cm, barely resorbed hb crystal. Age of one pyroclastic-flow deposit, middle of this group=470±80 y; another, beneath Kaliurang, 430±150 y.
4. Basaltic andesite lava
5. Soil (40 cm, surface unit @ MN-25)
6. Coarse, light-colored sand
7. Tan-gray ash, with one light-colored 12-cm-diameter hb-rich fragment
8. Deeply weathered clayey ash with lapilli
9. Brown clayey ash
10. Weathered yellow soil
11. Lapilli and ash fall, dense dark fragments, lighter-colored pumice(?) fragments produce a "salt and pepper" appearance.
12a. Light gray ash [several m thick]
12b. Ash-rich pumiceous pyroclastic-flow deposit, deeply weathered [20 m+ thickness]
13. Debris avalanche deposit, with brecciated megaclasts of lava and pyroclastic deposit in clast-derived matrix.
14. Dome-collapse pyroclastic-flow deposit; magnetic vectors of clasts coherent, normal. Age=1130±50 y.
15a. Pumiceous lapilli (fall, ripped by pf)
b. Fine ash
16. Lahar deposit, clasts with random paleomag. orientations
17. Tephra layers, including one with gray non-vesicular hb dacite and white hb dacite pumice. Ash cloud surge of 1330±130 yr stratigraphically near here
18a. Pyroclastic-flow deposit, with hb-(px?) andesite
18b. Coarse breccia, gray, hb- and px-andesite, heterolithologic
19. Basaltic andesite scoria at Telogo Muncar
20. Older lavas and intercalated pyroclastic flow breccias. At least 3 lavas and 3 pyroclastic-flow deposits, + an older tephra(?). [note: oldest lava exposed at Telogo Muncar, at the waterfall on path E of Kaliurang, cascades over flat lying steel-gray plag-px basalt, with plag's 2-4 mm long. No hb in this flow, but there is some hb in float.]



G. TURGO - KALI TRITIS - SLEMAN

1. 1994 pyroclastic-flow fan upslope from G. Turgo; ash-cloud surge wrapped around east side of G. Turgo.
2a. Dark brown soil, with sparse lapilli
b-d. 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.
4. 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.
5. Moderately well sorted, normally-graded, 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, dome-collapse pyroclastic-flow deposit. (tentatively, 7a-l and 8a-b = Slk)
-- 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.

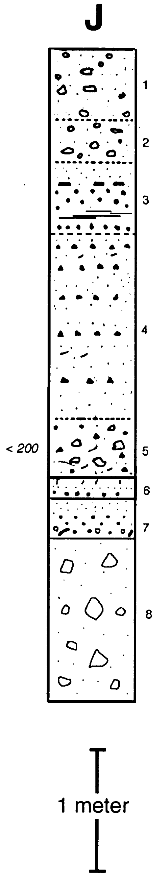
2. Yellow-brown, matrix-supported, indurated pyroclastic flow or lahar deposit. Heterolithologic, with rootless fumaroles or water escape pipes.

3. Brown, matrix supported breccia, with cross bedding and planar lamination. Pyroclastic flow or lahar deposit.

4. Ash
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)



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. Ash-cloud surge deposit?

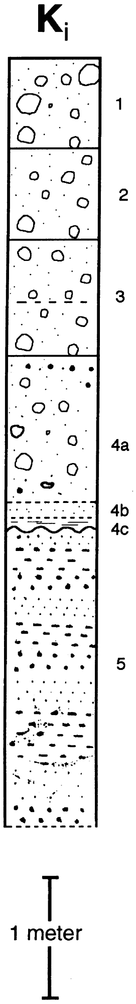
4. Reversely-graded, poorly-sorted breccia, with red, friable sandy matrix, indurated near top. Wood is charred near base of unit; partly charred near top.

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}.

Fig. 4. (*continued*)



KALI BLONGKENG - KALI PUTIH

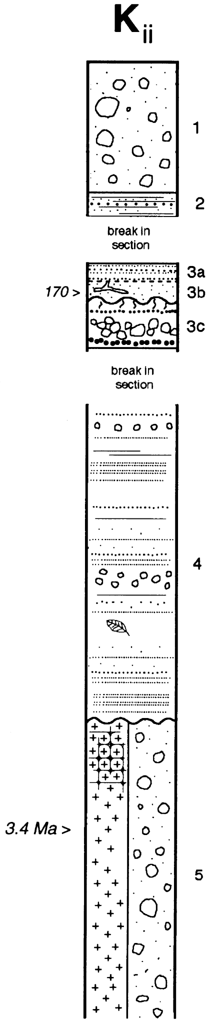
1. 1985 lahar deposit

2. 1984 pyroclastic-flow deposit

3. 1972-73, 1981, and other pyroclastic-flow deposits

4a 1969 pyroclastic-flow deposit, coarse, 4-m thick (not to scale)
b sandy strata with abundant charcoal
c fine gray ash with mm-scale laminae, probably from 1967-early 1969 activity

5. Multiple layers of tephra fall; yellow, ash and lapilli; clayey.



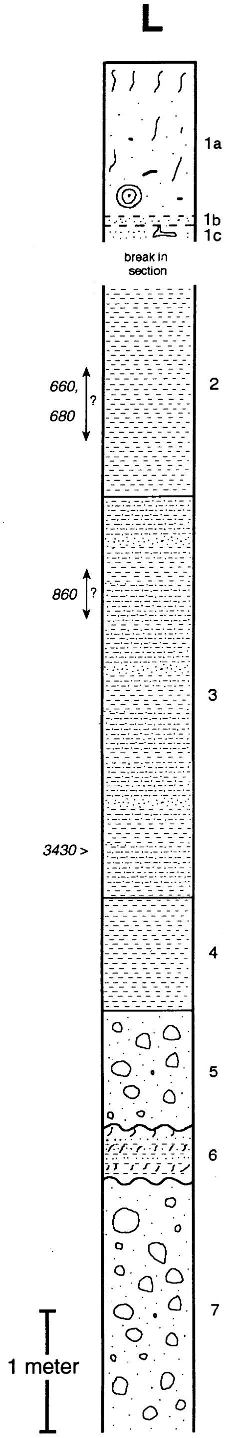
GUNUNG GENDOL (GENDOL HILLS)

1. 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.

3. (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 might be the plant-rich "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 hb-andesite lahar(?) breccia; G. Kremeng, behind Chinese cemetery, weathered hb-andesite float; G. Pring, in situ, orthogonally jointed (NOT jig-saw-fractured), 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*)



KALI PROGO; K. SILENG; BOROBUDUR

1a. Tan-brown ashy soil, with sparse charcoal bits, 2 m thick. Near Borobudur, shows modern-day formation of giant ant balls.

b. Discontinuous ash, 0-10 cm

c. Fine, light tan silty ash, bioturbated, 15-20 cm thick.

2. Oxidized yellow-brown clay, up to 5 m thick. Unknown origin; possibly upper sediment of Lake Borodubur. ^{14}C age from "volcanic sediment" (upper part of Lake Borobudur sediments?) is 660±110 y. Details of dated unit in Murwanto (1996).

3. Black to gray, organic-rich silt deposit. Widespread along K. Sileng; thickness typically 5-15 m, w/ some sub-horizontal internal stratification. Used by some residents as water source, though salty. Wood from upper part = 680 ± 95 y, 860±95 y (Murwanto, 1996); wood brought up from well at 13.5 m depth = 3430 ±50 yr (this paper)

4. Fine-grained, soft yellow clay below unit #3. May correlate with soft, brown tuff breccia found beneath unit #1 outside the area of lake sedimentation, or, alternatively, could be early, oxidized lake sediments.

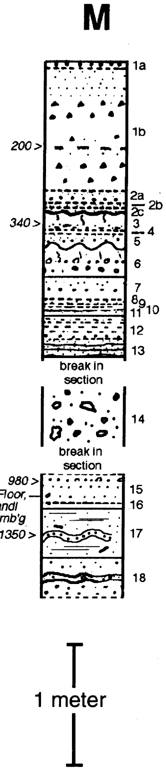
Note: "Dalle à plante" tuff of Berthommier (1990), also termed "blast deposit" by Camus et al, this volume, reportedly occurs along the Elo River. We did not see this outcrop, and do not know its stratigraphic position rel. to #1-4.

5. Older lahar deposits from G. Merapi. Exact stratigraphic position uncertain, but some of these could have blocked K. Progo and its tributaries, especially K. Sileng.

6. On the lower slopes of Menoreh Hills, multiple old, clayey tephra fall deposits, many with paleosols

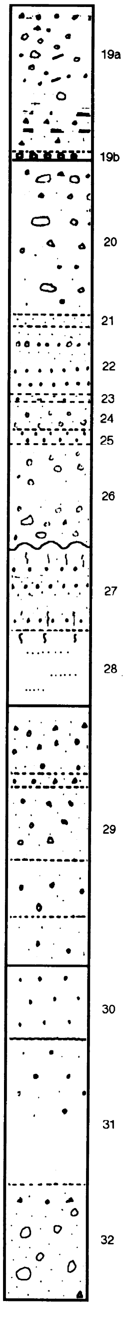
7. Hb-andesite breccias of Menoreh Hills, both lahar and pyroclastic flow origin.

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
3. Dark brown clayey soil developed on sandy ash with charcoal. 340 ± 100 yr
4. Brown clayey ash with weathered lapilli to 4 mm diameter
5. Brown coarse sandy ash, with granules and dark, dense lapilli to 1 cm dia
6. 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), Fe-staining, 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
11. Reddish lapilli to 3 cm dia in silty ash matrix, with small oxide and hb grains
12. 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 --
14. Pyroclastic-flow deposit that buried Candi Pendem. Age=980±80 ^{14}C y. Strat. correlation based on ^{14}C 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?)
17. Unconsolidated brown silt with mm to cm scale laminae. Pyroclastic surge deposit with lapilli to 1 cm diameter. Charcoal 1350 ± 200 yr



18. Ash cloud surge deposit overlying poorly sorted pyroclastic-flow deposit, with lapilli to 1 cm diameter

19a Brown indurated pyroclastic flow or lahar deposit, with lapilli to 2 cm diameter. Charcoal. Normally graded.
b Airfall lapilli and discontinuous fine gray silty ash at base of the abovementioned breccia

20. Breccia with tephra fall at base, as above, but with blocks to 10 cm diameter

21. Discontinuous, fines-depleted surge (?) deposit
22. Fines-depleted, reversely-graded pyroclastic flow(?) breccia. Pumiceous lapilli and blocks to 30 cm diameter, in poorly sorted, brown matrix
23. Light-colored tephra; dominantly granular but with a few pumices to 5 cm diameter
24. Brown lahar or pyroclastic-flow deposit
25. Lapilli fall unit
26. Brown lahar or pyroclastic-flow deposit

27. Yellowish-brown soil with several horizons of lapilli fall

28. Fine grayish-tan ash

[gap in exposures, ca 1-2 m]

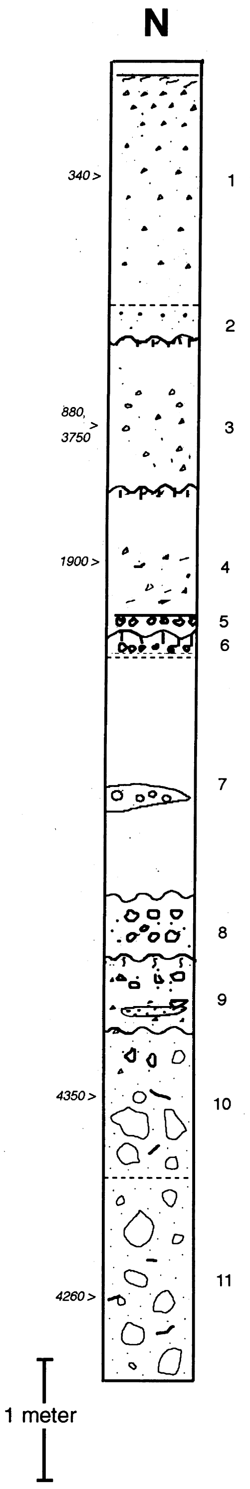
29. Coarse laharic breccia with some clasts larger than 1 m. Two to three m thick.

30. Dark brown unit of unknown origin on SE side of Pabelan River

31. Tan unit of unknown origin on SE side of Pabelan River

32. Brownish-gray laharic breccia

Fig. 4. (*continued*)



JRAKAH, KALI JUEH, KALI APU

1. Dense, indurated breccia, with light colored angular clasts, up to 50 cm diameter, in a dark matrix. Many casts of tree branches, but most are empty. Minor charcoal = 340 ± 70 yr. Weathered top. (Lahar deposit?)

2. White pumiceous lapilli fall. 2 cm thick in K. Jueh; correlative(?) unit 30 cm thick in Kali Apu.

3. Light gray pyroclastic-flow breccia, with subangular to subrounded clasts in loose matrix. Abundant charcoal from single outcrop and layer yields ages of 880 ± 60 yrs and 3750 ± 80 yrs. Quarried in Kali Jueh.

4. Pyroclastic-flow deposit in K. Apu. Gray, pumiceous, age=1900±80 y. Stratig. relation to N-3 uncertain.
5. Pumiceous lapilli fall, white
6. Yellow lapilli fall deposit.

7. Massive fine-grained ash, baked and indurated at top. 7 m thick (not to scale). Contains conglomeratic lens 1.5 m thick, dark gray, with clasts up to 40 cm dia.

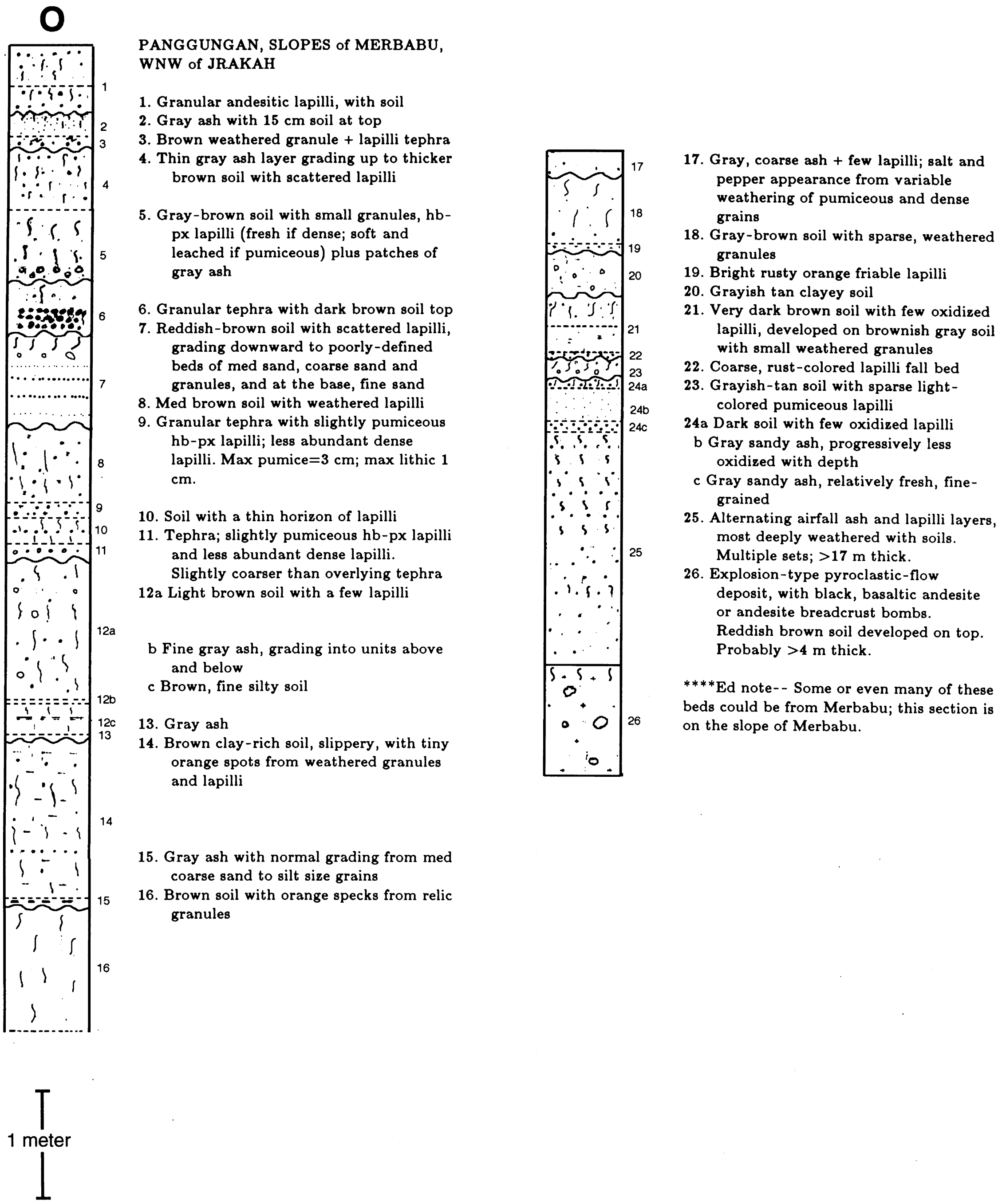
8. Conglomeratic lahar deposit, 2 m thick.

9. Brown pyroclastic flow breccia, with clasts of px andesite to 40 cm diameter, in matrix of same. In one outcrop, has lens of coarse conglomerate. Soil at top.

10. Dry, friable, brown pyroclastic flow(?) breccia with clasts up to 40 cm dia in fine matrix. Charcoal=4350 ± 70 yrs.

11. Moist, brown pyroclastic flow(?) breccia, with clasts of up to 40 cm diameter in fine matrix. Charcoal = 4260 ± 80 yrs.

Fig. 4. (*continued*)



PANGGUNGAN, SLOPES of MERBABU, WNW of JRAKAH

1. Granular andesitic lapilli, with soil
2. Gray 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
5. Gray-brown soil with small granules, hb-px lapilli (fresh if dense; soft and leached if pumiceous) plus patches of gray ash
6. Granular tephra with dark brown soil top
7. 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
8. Med brown soil with weathered lapilli
9. 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 soil with orange specks from relic granules
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

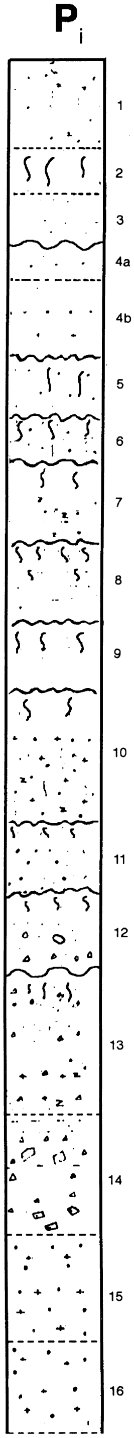
b Gray sandy ash, progressively less oxidized with depth

c Gray sandy ash, relatively fresh, fine-grained

25. 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.

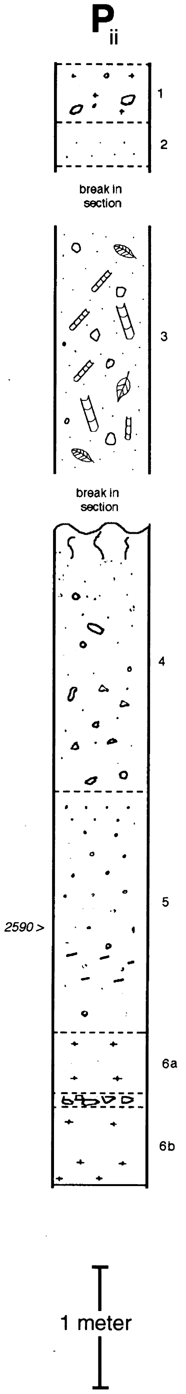
****Ed note-- Some or even many of these beds could be from Merbabu; this section is on the slope of Merbabu.

Fig. 4. (*continued*)



CEPOGO, SE of K. Kenting bridge

1. Multiple layers of tephra fall. 4 m thick. Ash + lapilli to 0.5 cm diameter. Max thickness of individual beds, 10-15 cm. Slightly weathered.
2. Brown soil (1.2 m)
3. Grayish-tan clayey ash with a few pumice fragments. Possible pyroclastic-flow deposit? (0.9 m)
4a. Dark brown soil with a few pumice fragments
b. Light tan soil with weathered px-hb andesite or dacite pumice; fresh euhedral px crystals
5. Brown soil with a few lapilli
6. Brown soil with sparse lapilli; dark, organic-rich top
7. Brown soil with weathered lapilli.
8. Brown soil, w/ dark brn organic-rich top and reddish-tan clayey, lapilli bearing base
9. Light-colored ash, on which brown soil with blocky texture and dark organic-rich top have developed.
10. Ash, with weathered andesite lapilli; brown soil developed on top.
11. Granular tephra, light gray, pumiceous, slightly weathered, salt and pepper appearance; dark brown indurated soil developed at top.
12. Granular tephra; dark brown soil top.
13. Weathered andesite breccia, with fine, yellow-brown matrix; brn soil at top.
14. Pyroclastic flow(?) breccia, unstratified. Plag-rich basalt or andesite scoria in yellow-tan, slightly clayey matrix
15. Crudely-stratified, fines-depleted augite basalt scoria. Plag not conspicuous. Top few meters have abundant large, free, euhedral augite crystals. Fall(?) or surge(?).
16. Poorly-sorted basaltic scoria, dipping 20°E. Augite crystals present but less abundant than above



CEPOGO, NW + downstream of K. Kenting bridge

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

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

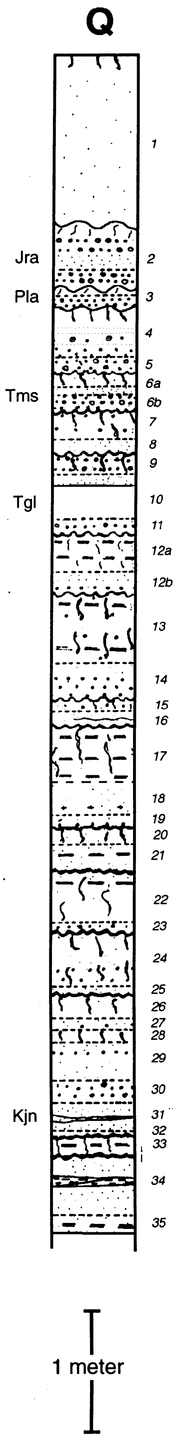
3. Indurated, 3 to 5-m-thick surge(?) or fine-grained lahar(?) deposit with abundant bamboo molds, leaf molds. Wood was not charred and thus not preserved. Relatively young, because no other deposits found on top. (=the so-called "blast" deposit of Camus et al, this volume) (possibly = Tms or Tgs?)

-- break in section

4. Coarse laharic breccia; locally brown and indurated, with soil at top; elsewhere gray, unconsolidated. Magnetic vectors in clasts are random.
5. Unconsolidated pumiceous hb andesite pyroclastic-flow deposit. Gray and white banding in pumice, probably as function of vesicularity. Abundant charcoal, 2590 ±120 yr BP.

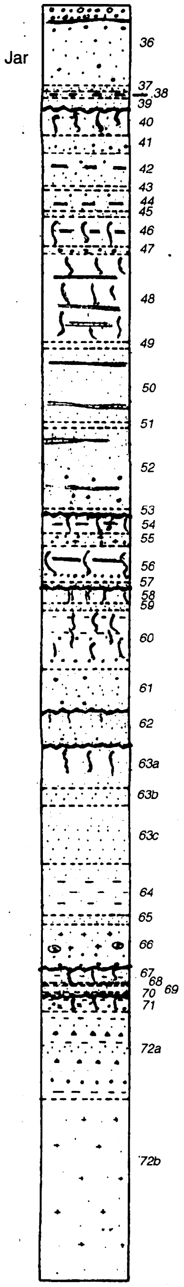
6a. Px-rich lava flow, upper of 2 flow units, separated from lower unit by flow rubble
b. Px-rich lava flow, lower of 2 flow units. Relatively fluid flow that reached 5 km from G. Bibi or 8 km from G. Merapi.

Fig. 4. (*continued*)



WONODJOJO

1. Soil, with some light-colored ash but no distinct ash layers (2 m thick)
2. Andesitic tephra fall, rel. dense lithic rich, dark gray, several layers (=Jra)
3. Lapilli + granules, fines-poor, with euhedral px; salt/pepper-like (=Pla)
4. Planar-bedded, fine, light-gray ash with abundant accretionary lapilli; soil top
5. Hb pumice lapilli, with some gray/white banding (units 5+6 together = Tms)
6a. Gray ash with soil at top
b. White and gray banded pumice lapilli
7. Brown soil with scattered lapilli
8. Gray, med-coarse sandy ash
9. Brown soil with a few hb-dacite pumice lapilli as large as 4 cm dia near top
10. Fine, finely-bedded, indurated, sometimes pink, ash with accretionary lapilli
11. White, slightly weathered pumiceous lapilli, up to 6-cm-dia. Hb-rich, with possible compositional banding (layers 9-11, together, = Tgl)
12a. Brown silty soil
b. Indurated gray ash, in which layers of accretionary lapilli ash alternating with structureless ash. Fe-stained
13. Light brown silty soil, with lapilli throughout (colluvium or overbank pyroclastic-flow deposit)
14. Pinkish-gray indurated ash with lapilli near top; Fe-staining
15. Fe-stained soil with few white lapilli
16. Rusty to gray indurated ash; 1 or 2 layers.
17, 18. Light gray fine ash, w/ fragment of dense, glassy, flow-banded andesite with sparse Fe-Mg minerals; soil top
19. Gray, indurated, fine ash, with lapilli to 2 cm diameter. Top 1 cm = dark gray ash
20, 21. Slightly indurated gray ash, reverse-graded from silt to med sand; soil top.
22. Light brown silty soil; ash-rich
23. Lapilli, pumiceous (gray, to 4 cm dia) and dense lithics (to 2 cm dia)
24. Tan ash-rich soil, with minor lapilli (ash cloud deposit?) (0.65 m thick)
25. Indurated light gray fine-sandy ash
26, 27. Indurated accretionary lapilli ash, discontinuous, soil on top
28. Indurated light brown soil
29. Sand and lapilli to 1 cm diameter, plag-rich with minor px, minor charcoal
30. Yellow-tan soil with white pumiceous lapilli at top, max 4, avg 1 cm diameter
31. Fine gray ash, with pink accretionary lapilli, sandy laminae, and spots of Fe-oxide staining. Surge deposit? (=Kjn)
32. Pinkish-gray sandy ash
33. Brown-tan silty soil
34. Clayey, laminated fine ash, with Fe-stained bedding planes

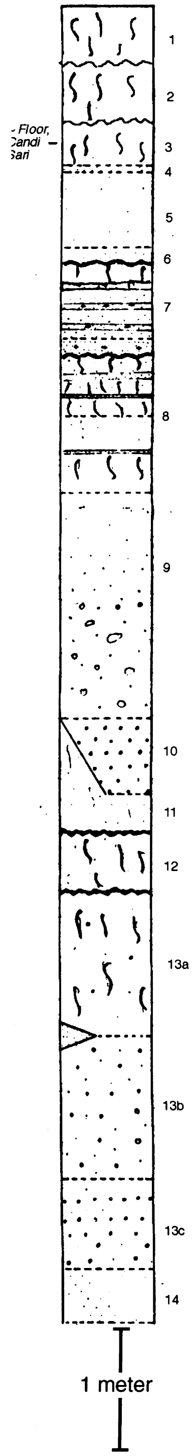


35. Pinkish or violet-gray silty ash
36. Light gray ash. Finely laminated, locally indurated, with accretionary lapilli. White pumiceous lapilli at top. (=Jar)
37. Light gray, indurated sandy ash
38. Bright orange silty ash
39. Rust-spotted gray ash
40, 41. Alternating gray ash and coarse sand or granules, w/ Fe-staining along bedding planes; oxidized soil at top
42. Tan silty ash, with sparse lapilli at top. Ash-cloud surge deposit?
43. Fine gray ash
44. Tan, silty ash with white lapilli at top.
45. Gray, med-fine sandy ash
46. Tan, silty soil, with white lapilli at top. Ash-cloud surge deposit?
47. Creamy-white weathered or altered hb-px dacite(?) pumice lapilli
48. Tan-brown silty soil with rusty flecks
49. Fine gray ash
50. Tan-light gray (or pink?) silty ash with pockets of underlying ash
51. Discontinuous light gray fine sandy ash
52. Tan-pinkish gray silty ash-cloud surge deposit, with a few sparkling white sugary-textured clasts, plag or glass, 2-3 cm in diameter, + tiny black xls
53. Discontinuous layer of gray silty ash
54. Brown silty soil, with minor clay + specks of plag, small pumice granules
55. Dark gray, angular andesitic lapilli
56. Gray brown silty soil with layer of yellow lapilli
57. Discontinuous gray ash and lapilli
58, 59. Gray fine sandy ash, soil on top
60, 61. Indurated dark gray ash, med sand, with blocky fractures resembling lapilli. Sparse yellow scoriaceous lapilli. Soil top
62. Gray ash, normally graded from coarse to fine sand, with soil at top
63 Sandy gray ash, brown soil at top
64. Tan clayey ash with weathered plag
65. Fresh gray, med sandy ash
66. Andesitic scoria fall. Grayish brown coarse sand and granules, + a few lapilli to 1 cm diameter. Mostly fresh, but with a few cream-colored weathered lapilli
67. Pinkish(?)-brown clayey soil, with pockets of gray ash and weathered lapilli
68. Fine light gray, clayey ash
69. Pinkish brown clayey soil; sparse lapilli
70. Fine light gray-pink clayey ash
71. Dark brown clayey soil with scattered 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

Fig. 4. (*continued*)

R

GEDANGAN/ CANDI SARI



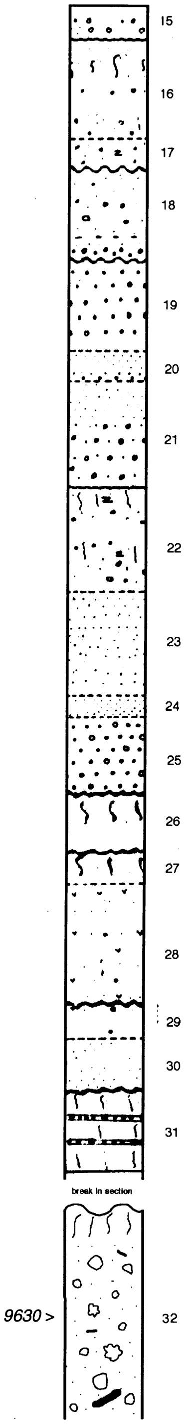
1. Lumpy soil, with lots of roots
2. Light tan ash-rich soil
3. Brown soil [Floor of Candi Sari within unit R-3]
4. Discontinuous gray ash
5. Yellow-brown ash-rich soil
6. Gray sandy ash
7. Yellow-brown soil with some andesitic ash layers (?)
8. Light tan ash, with interbedded soils
9. Light tan ash, with occasional yellow-cream-colored pumiceous lapilli
10. Lens of loose granules, lapilli, andesitic lithics. Channel fill?
11. Gray ash with soil top
12. Brown organic rich soil

13a Brown soil, with weathered pumiceous lapilli.

b Lens of coarse sand, gravel

c Pumiceous lapilli fall

14. Gray-tan ash with golden orange oxidation stain. Well stratified, average bed thickness about 1 cm



15. Pink-gray ash with pumiceous lapilli
16. Dark soil, possibly developed from underlying unit
17. Deeply weathered pumiceous lapilli
18. Deeply weathered golden pumice lapilli, with soil at top
19. Med brown soil with scattered lapilli (pumiceous and dense lithics)
20. Abundant lapilli in brown ash (tephra fall?)
21. Bright pink and orange ash beds, with occasional interbeds granules. Tephra fall.
22. Soil, with small weathered pumiceous lapilli, especially near the base of the bed
23. Moderately indurated, fresh sand and small dense lithic lapilli; pinkish top.
24. Pinkish-gray ash (multiple thin beds)
25. Brown soil with minor pumice lapilli
26. Dark brown organic rich soil
27. Golden brown soil
28. Slightly indurated tuff, ash + lapilli; only moderately sorted but probably tephra fall
29. Pumiceous lapilli tuff (fall deposit); soil top
30. Moderately fresh granules and coarse sandy ash. Ash is light gray to white, rich in glass shards, hb + px
31. Brown soil with at least 1 or 2 interbeds of pumiceous lapilli fall.

... (break in section) ...
(unit of uncertain stratigraphic position):

32. Friable, fines-depleted, dark-gray pyroclastic-flow deposit. Sandy matrix with moderately abundant bombs and occasional large charred logs (9630 ±60 y, the oldest age that we have obtained from Merapi). Base of exposure, quarry, Sumbung, Cepogo

Fig. 4. (*continued*)

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

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
2000 A.D.	New Merapi	Summit lavas	New Merapi	Young Merapi	Historical Merapi		NEW MERAPI^{b}
		– 1888 A.D.^{a} –			– 0.5 ka –	Pasarbubar^{c}	– relatively weak 20th century
						Kepuharjo	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
1000 A.D.	– 1006 A.D.^{d}	– 1006? A.D.^{d} –					– more large explosive eruptions
			– 928 A.D.^{e} –			Muntilan	– 928 A.D.^{d,e} Mataram civilization
						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
					Merapi	Tosari	side^{b}
					(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 (*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 westward-directed 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, 20-m-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, near-source 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 $= 9630 \pm 60$ ^{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 ^{14}C 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 phenocryst-rich basaltic lavas that contain more hornblende than augite, though one young basaltic andesite lava (52.7% SiO_2) 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 ~3430 ^{14}C y B.P.; (b) two lakes, one formed and filled ~3430 ^{14}C y B.P. and another formed and filled in the same area ~860–660 ^{14}C y B.P. (~1200–1400 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 ^{14}C 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 ± 120, 1700 ± 120 and 1840 ± 150 ^{14}C y B.P.). If the vent

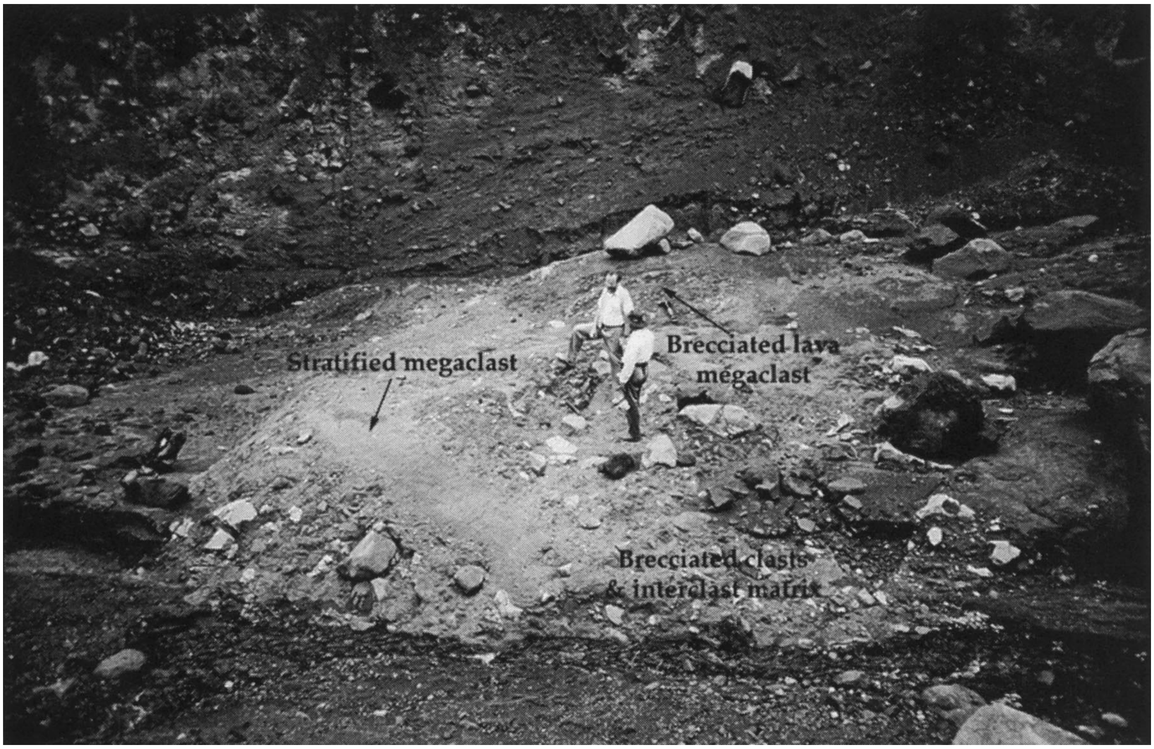


Fig. 5. Debris avalanche deposit, Kali Boyong valley. Megaclasts of brecciated lava and stratified pyroclastic material occur in a matrix of brecciated smaller clasts, sand and clay.

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 ~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 m^3 of sediment each year, which would bring between 10^9 and 10^{10} m^3 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 km^2. 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 $\geq$ 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 valley-filling 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

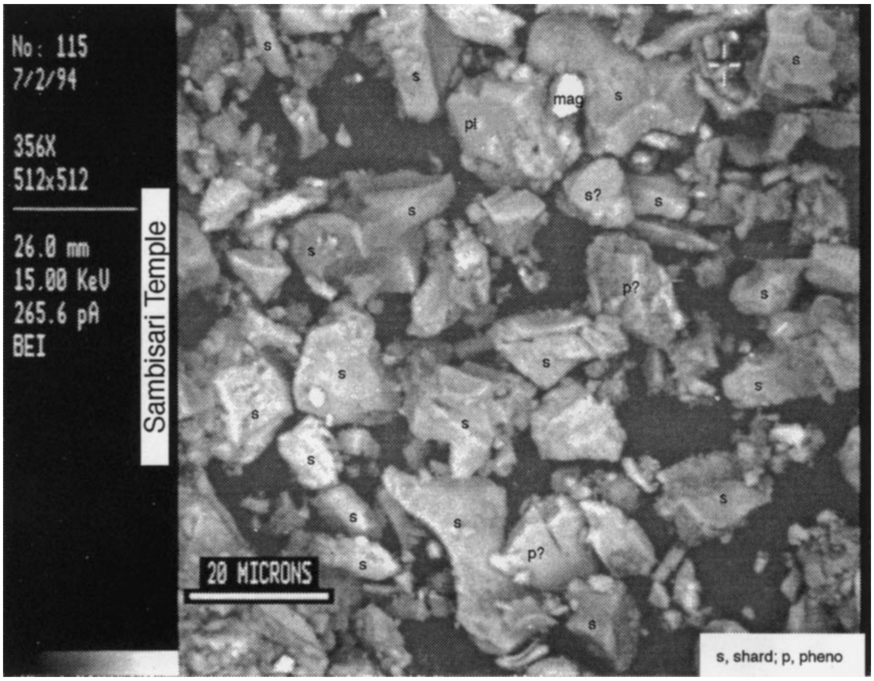


Fig. 7. Scanning electronic microscope image of fine ash that immediately overlay the floor of Candi Sambisari (Fig. 4, unit E_i-15). Sample was taken from the eastern cutbank of the temple excavation, at the level of the temple floor, shortly after the excavation was completed and before subsequent 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 dome-collapse 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-meter-thick 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 ~25 μm (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 "co-ignimbrite" 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 pyroclastic-flow 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 bread-crust 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 ± 50 ^{14}C y old, which implies that this debris avalanche cannot be from the somma-forming collapse of ~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 ~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 ~660 ^{14}C y B.P.; or (b) two lakes, one formed and filled ~3430 ^{14}C y B.P. and another formed and filled in the same area ~860–660 ^{14}C y B.P. (~1200–1400 A.D.). The record of deposits is ambiguous. A change from black to yellow deposits indicates that by ~660 ^{14}C y 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 ± 95 and 680 ± 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 matrix—which 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 ^{14}C 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 ^{14}C y, 1σ 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 (~740 ± 50 ^{14}C y (~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 ~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 ~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 explosion-type 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.

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