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Historical eruptions of Merapi Volcano, Central Java, Indonesia, 1768–1998

B. Voight[a,b,*], E.K. Constantine[a], S. Siswowidjoyo[c], R. Torley[d]

[a]Department of Geosciences, The Pennsylvania State University, University Park, PA 16802, USA
[b]US Geological Survey, Cascades Volcano Observatory, Vancouver, WA, USA
[c]Volcanological Survey of Indonesia, Jn. Diponegoro, Bandung Indonesia
[d]Department of Geology, University of Oregon, Eugene, OR, USA

Abstract

Information on Merapi eruptive activity is scattered and much is remotely located. A concise and well-documented summary of this activity has been long needed to assist researchers and hazard-mitigation efforts, and the aim of this paper is to synthesize information from the mid-1700s to the present. A descriptive chronology is given, with an abbreviated chronology in a table that summarizes events by year, assigns preliminary Volcanic Explosivity Index (VEI) ratings and Hartmann classifications, and provides key references. The history of volcano monitoring is also outlined.

The study reveals that a major difference in eruption style exists between the twentieth and nineteenth centuries, although the periodicity between larger events seems about the same. During the twentieth century, activity has comprised mainly the effusive growth of viscous lava domes and lava tongues, with occasional gravitational collapses of parts of oversteepened domes to produce the nuées ardentes—commonly defined as “Merapi-type”. In the 1800s, however, explosive eruptions of relatively large size occurred (to VEI 4), and some associated “fountain-collapse” nuées ardentes were larger and farther reaching than any produced in the twentieth century. These events may also be regarded as typical eruptions for Merapi. The nineteenth century activity is consistent with the long-term pattern of one relatively large event every one or two centuries, based on the long-term eruptive record deduced by others from volcanic stratigraphy. It is uncertain whether or not a “recurrence-time” model continues to apply to Merapi, but if so, Merapi could soon be due for another large event and its occurrence with only modest (or inadequately appreciated) precursors could lead to a disaster unprecedented in Merapi’s history because the area around the volcano is now much more densely populated. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Merapi Volcano; Java; lava dome eruption; nuées ardentes; pyroclastic flows; dome-collapse; fountain-collapse; volcanic earthquakes; eruption precursors; hazard mitigation

1. Introduction

Merapi Volcano, located within heavily populated central Java, is one of the Earth’s most active and feared volcanoes (Figs. 1 and 2). Almost half of Merapi’s nearly 80 reported historical eruptions are known to have been accompanied by nuées ardentes—more than any other volcano. About a dozen of these nuées have caused fatalities (SEAN, 1989; Simkin and Siebert, 1994).

A vital aspect of volcano hazard evaluation involves the reconstruction of the volcano’s past

* Corresponding author. Tel.: + 1-814-238-4431; fax: + 1-814-863-7823.

E-mail address: voight@ems.psu.edu (B. Voight).

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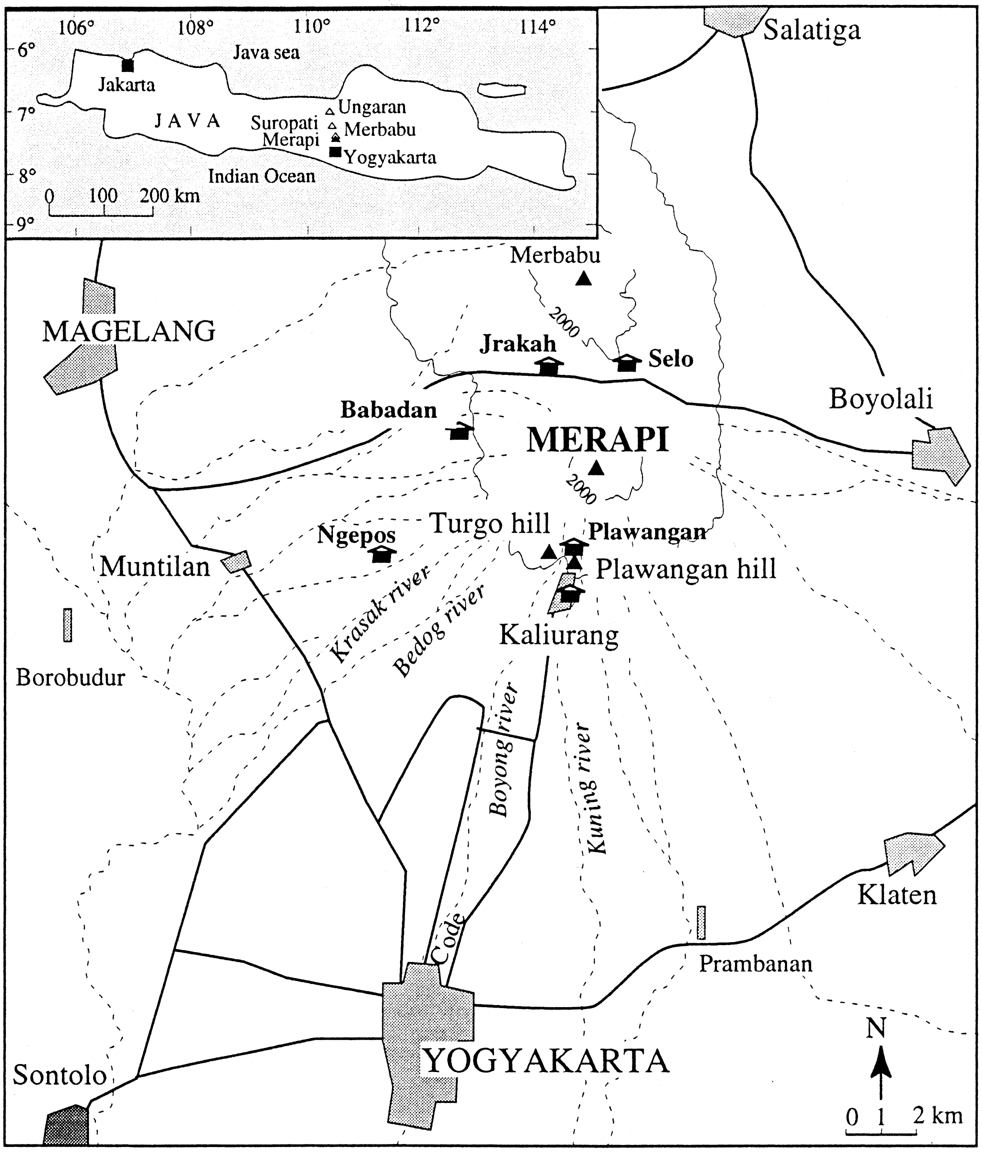


Fig. 1. Location map of the Merapi area, showing major towns and villages (black patches) and Volcanological Survey of Indonesia observation posts (hut symbols) (after Abdurachman et al., 2000 – this volume). Solid lines are main roads, dashed lines are main valleys. Black triangles indicate the Merapi summit, Turgo and Plawangan hills on the south flank above Kaliurang, and Mt. Merbabu. Inset map shows location of Merapi volcano in Java.

history, establishing a chronology of hazardous events, detailing recurrence frequencies and changes in eruptive style, and searching for evidence of cyclicity. Companion papers in this volume approach this reconstruction mainly from stratigraphy and geochronology, and trace the prehistoric Merapi far back in time (Andreastuti et al., 2000 – this volume; Camus et al., 2000 – this volume; Newhall et al., 2000 – this volume). Our paper complements these papers by focusing on the historical observations of the past two centuries.

Our objective is to compile a comprehensive

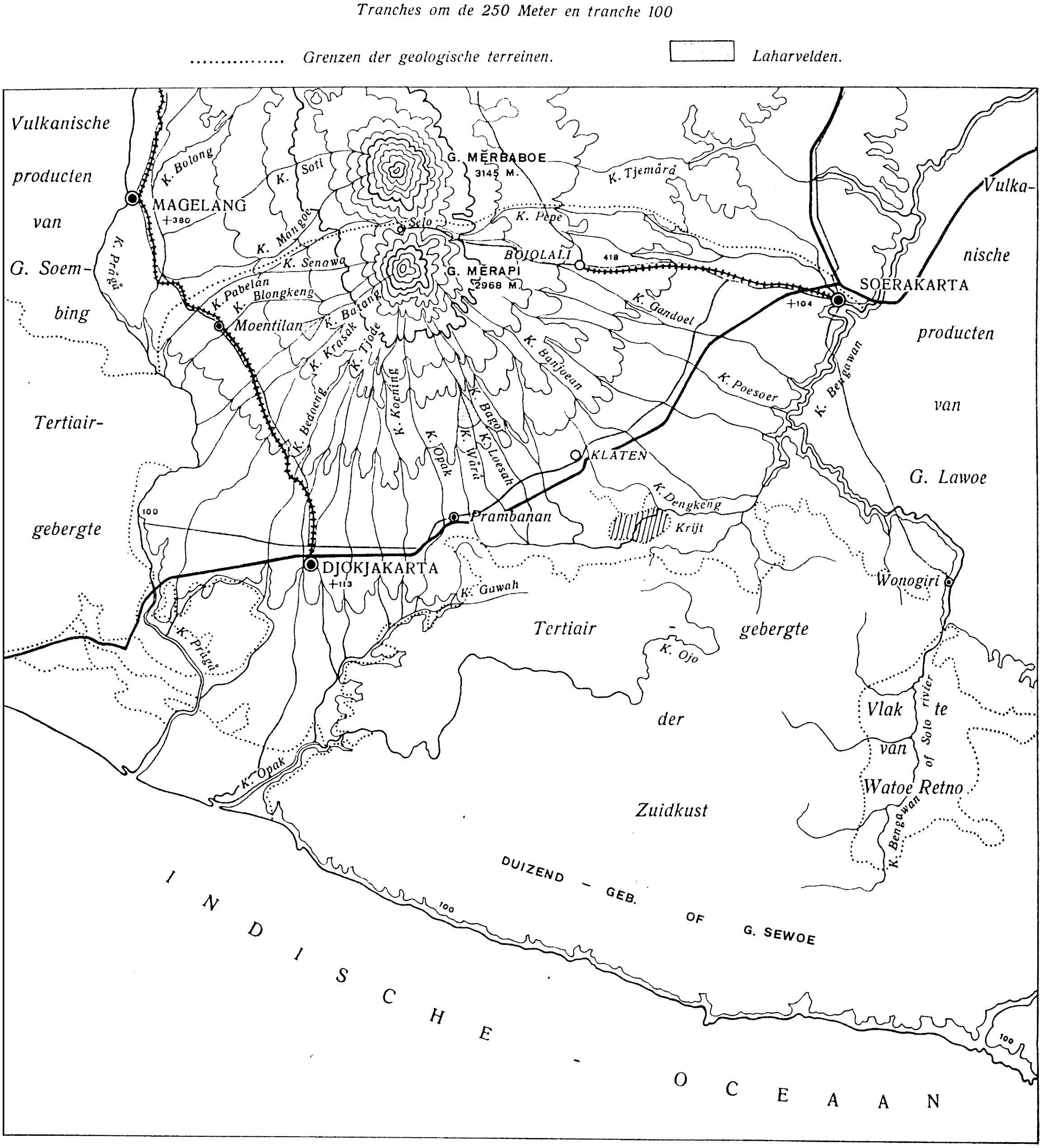


Fig. 2. Location map of the Merapi and Merbaboe area, showing river and place names, with names in Dutch style as used in most early reports (Kemmerling, 1921). Lahar deposition areas stippled. Dashes separate other geological terrain, including Tertiary deposits on the west and south, and deposits from volcanoes Soembing, Merbaboe, and Lawoe on the northwest, north, and east, respectively. "G." indicates "*Gunung*" (mountain).

descriptive history of recent eruptive growth and destructive activity at Merapi Volcano, based on information gathered from many sources. Early literature (pre-World War II) is found mainly in Dutch and German publications, with pioneering descriptions by Junghuhn (1853–1854) and Verbeek and Fennema (1896). Observations and research became systematic in the first half of the twentieth century, with the important contributors including Hartmann, Kemmerling, Neumann van Padang, Petroeschevsky, Stehn, Taverne, and Van Bemmelen (see the References). These workers also compiled details for a number of nineteenth and early-twentieth century eruptions.

Since 1927, information on volcanic activity has been recorded in Bulletins of the Netherlands East Indian Volcanological Survey (BNEIVS), the forerunner organization for today's Volcanological Survey of Indonesia (VSI). The continuity of this enterprise has been maintained, remarkably, even through World War II and the post-war fight for independence. Thus VSI celebrated its 75th Anniversary in 1995. Indeed, a *de-facto* "Volcanological Survey" has existed since 1918, first as a "Volcanological Commission" established by the *Natuurkundige Vereenigung* in Batavia (Jakarta) that supported work by Kemmerling. After the Kelud eruption in 1919, a "Volcano-Watching Service" was formed under the Department of Mines (Neumann van Padang, 1983).

Much work is scattered or located in remote sources (see bibliography in Kusumadinata, 1979). Some of this material was gathered by the US Geological Survey in the 1980s, in their collaborative work with VSI. Other historical summaries are recorded in Van Bemmelen (1949); Neumann van Padang (1951, 1983); Berthommier (1990); Berthommier and Camus (1991). This paper builds on the previous work and synthesizes the information available for the period from the mid-1700s to the present. Our aim is to provide a concise documented reference source to aid current and future research and hazard-reduction efforts at Merapi. A descriptive narrative is given, along with an abbreviated chronology that summarizes events by year, Volcanic Explosivity Index (VEI), Hartmann eruption classification, and key references.

Illustrations are taken largely from original sources. We have not generally altered these documents, as there is some merit to preserving the original forms. However, in some cases, the scale of some lettering made words difficult to decipher, and we have increased font size. Also in most cases the language is something other than English, so we provide detailed descriptions, and translated figure legends, in captions for the convenience of the reader. Likewise we have not altered the place-names on these documents, which therefore vary to some degree according to the language used (e.g. the towns Boyolali, and Yogyakarta of Fig. 1, are found on the Dutch colonial maps as Bojolali, and Djokjakarta). The Dutch orthography "oe" is equivalent to "u", as in Moentilan, or Muntilan. In general these adjustments should provide little problem. On many maps, the place-name abbreviations "G.", for "Gunung" (mountain), and "K.", for "Kali" (river), are used.

2. Background

2.1. Terminology for Merapi case descriptions

Descriptions of Merapi eruptions have involved descriptions in six languages (Javanese, Indonesian, Dutch, German, French, and English) and have generated an ornate *batik* of terminology. New terms have been introduced, and many of these have been used in different senses by various authors. A number of these terms deal with phenomena associated with lava-dome growth and destruction, processes characteristic of recent Merapi activity. We define and discuss these terms as they apply to the case descriptions.

Lava domes are thick, bulbous, usually volatile-poor masses of highly viscous lava. The Merapi andesites typically contain 30–50 vol% phenocrysts and are as much as 75 vol% crystalline including microlite growth (Hammer et al., 2000 – this volume); thus the liquids (or groundmass glasses) present have highly evolved (rhyolitic) composition, which together with crystallinity accounts for the high viscosity. On a sufficiently steep slope, dome lobes can grade into lava flows, or *coulées*, defined as stubby flows transitional between conventional flows and domes (Van Bemmelen, 1949, p. 197; Francis, 1993, p. 155). When lava domes, coulées, or flow snouts grow beyond specific limits related to strength, thickness and slope, they can fail by gravitational collapse. This situation gives rise to "Merapi-type"

Table 1
Classification of commonly used terms for nuées ardentes

Lacroix (1930)	Escher (1933a); Macdonald (1972)	This study	Formation mechanism
Nuées ardentes d'avalanche	Merapi-type glowing clouds/ pyroclastic flows	Dome-collapse nuées ardentes	Dome-collapse
Nuées ardentes d'explosions vulcaniennes	St. Vincent-type pyroclastic flows	Fountain-collapse nuées ardentes	Collapse of a vertically erupted debris fountain
Nuées peléennes d'explosion dirigée	Glowing clouds by directed blasts	Directed-explosion nuées ardentes	Directed blast

glowing clouds or *nuées ardentes* (Escher, 1933a,b; Macdonald, 1972), terms conventionally used world-wide to indicate pyroclastic flows produced by gravitational failure. Eruptions in 1942–1943 at Merapi have been cited as classic examples of this phenomenon (Francis, 1993, p. 250), but the original recognition of this type derives from Escher's (1933a) interpretation of the dome-collapse pyroclastic events of 1921–1922 (Kemmerling, 1921). Other terms for similar phenomena include *awan panas guguran*, or *nuées ardentes d'avalanche* (Lacroix, 1904). *Awan panas* (lit., hot cloud) is the Indonesian word-equivalent of nuée ardente, and the Javanese term *wedus gembel* (lit., wooly sheep) is the locally-used central Javanese equivalent. Table 1 lists word equivalents; additional information on comparative terminology is provided by Smith and Roobol (1982) and Newhall et al. (1999).

Dome-collapse nuées ardentes have been subdivided into two types by Bardintzeff (1984) as Merapi-type and "Arenal-type", with the former presumably occurring without fresh glass, and the other containing pumiceous glass, respectively. However, we follow the convention of most authors to consider as Merapi-type any dome (or steep lava flow) collapse-induced pyroclastic flow (Macdonald, 1972; Francis, 1993), without presuming to assume whether or not the collapsing lava was fully crystallized or had small residual pockets of partly molten material. In general, the interior lava in many fresh domes probably have around 5–10 vol% or more still-molten material.

Relatively small lava-block rockfalls are distinguished from nuées ardentes by smaller size, lesser runout, less fines, and lack of appreciable convecting hot clouds. The local name for these common phenomena is *Guguran*.

Pyroclastic material from Merapi-type dome failures is distributed usually in relatively narrow sectors defined by the approximately radial valley systems. Active sectors can shift over time because of changes in vent location and (or) erosional or constructional changes affecting the position of low areas along the crater rim (Newhall et al., 2000 – this volume).

Also common at Merapi is the "St. Vincent-type" nuée ardente (Escher, 1933a; Macdonald, 1972), in Indonesian, *awan panas letusan*, and otherwise known as a *nuée ardente d'explosion vulcanienne* (Lacroix, 1904). These flows result from the collapse of a nearly vertical eruption fountain of pyroclastic debris and gas. Flow direction is influenced by the vent geometry and location, possibly the wind direction, and the topography of the summit region onto which the debris descends. Breaches or low points in the rim of the crater can direct the pyroclastic current to a particular sector, but generally the distribution of pyroclastic currents is much broader that for a dome-collapse event. These events have also been called *explosion-type nuées ardentes* (Neumann van Padang, 1933; Van Bemmelen, 1949), although this term can be confusing as it does not discriminate between fountain-collapse and "Peléean-type" nuées generated by non-vertical explosions. Angular lithic clasts, and breadcrust bombs and scoria, if fresh magma is involved, are often cited as being characteristic of the St. Vincent-type nuées ardentes deposits, although, as the 1997 eruptions on Montserrat have demonstrated, pumice can also be produced. Moderately large explosive eruptions of this type occurred in 1822, 1832, 1846, 1849, and 1872 (Hartmann, 1935a; Zen et al., 1980), and in 1969 (BVSI, no. 106).

Grandjean (1931a–c) argued that a third type of pyroclastic flow occurred at Merapi in 1930, called the *nuées peléennes d'explosion dirigée*, or Peléean-type nuées ardentes, which are glowing clouds generated by directed blasts (Lacroix, 1904, 1930). The occurrence of such a process driving the 1930 Merapi eruption was disputed by Neumann van Padang (1933) and some others. Table 1 organizes these terms and classifications.

To simplify the case descriptions in this study, we generally consider only two types. The first is the dome-collapse nuée ardente, caused by collapse and fragmentation of a growing unstable lava dome or coulée and usually affecting a relatively narrow sector on the volcano flank. Material breaks off of the snout of the dome or dome-flow, causing an avalanche of material down a path on the Merapi slope. The second is the fountain-collapse nuée ardente, caused by collapse of a near-vertical eruption fountain and sometimes capable of affecting a much broader sector, or multiple sectors, on the volcano flank(s). If information about the event is uncertain, we do not assign type. The recognition of type is not always obvious, even when photographic documentation of the eruption plume is available.

The dense basal parts of pyroclastic currents at Merapi generally follow narrow, steep-sided river channels that have been carved into the alluvial apron (Newhall et al., 2000 – this volume). Such a channelized flow, called *ladu* by the Javanese (Kemmerling, 1921; Neumann van Padang, 1933; Van Bemmelen, 1949), has the capability to locally spill over its containment channels onto flat, interfluve surfaces. The overbank flow deposits are usually finer grained and better sorted than their channeled facies, although on occasion enormous lava blocks are dropped by this mechanism on interfluves. All types of pyroclastic flows at Merapi may develop channelized and overbank facies. Fountain-collapse nuées ardentes can be relatively voluminous and commonly have more extensive overbank deposits than dome-collapse nuées. Ash-cloud surges, which are dilute rapidly moving ash clouds generated from ground-hugging pyroclastic flows of any type, are found in association with both dome-collapse and fountain-collapse nuées, and may spread over interfluves far beyond the channel boundaries. These are highly dangerous phenomena, even though the resulting deposits may be thin and are commonly not preserved (Abdurachman et al., 2000 – this volume). Likewise, ash-fall deposits are also found in association with plumes rising from pyroclastic flows and surges.

Lahars, the Javanese term for debris flows and hyperconcentrated flows, are common at Merapi, where they are usually caused by rainstorm mobilization of loose pyroclastic debris on the volcano flank. Merapi lahars can range from thick sediment-rich slurries that support large boulders, to, more commonly, hyperconcentrated streamflows with noisy turbulent boulder transport (Schmidt, 1934; Lavigne et al., 2000a,b – this volume). The term *banjir* indicates a muddy streamflood, which sometimes can evolve downstream from lahars that have dropped their bedload or can be produced by storm runoff that is heavy but insufficient to support more concentrated sediment flows (Neumann van Padang, 1933; Newhall et al., 2000 – this volume).

2.2. Hartmann's classification

Hartmann (1935a) believed that the Merapi eruptions seemed to evolve according to several general patterns. (He used the term "cycle" in his description, but we avoid this term because it implies a regular repetition of processes over some characteristic time period; its usage has confused many students of Merapi volcanism.) Hartmann classified activity into four groups, which he inferred to be related to the gas content of the erupting magma. The classes, A, B, C, and D, were arranged in order of increasing explosivity. Hartmann's classification has been used by many researchers at Merapi (e.g. Van Bemmelen, 1949, pp. 199–200), although a few authors have reported problems in application (e.g. Ratdomopurbo and Poupinet, 2000 – this volume). Because of its extensive use to describe the relative size and character of Merapi eruptions, the classifications are reviewed below (Hartmann, 1935a, see Table 4; 1935b, Table p. 204; Van Bemmelen, 1949); we add other interpretation criteria.

Class A activity is associated with gas-poor magma which rises through the vent and spreads itself into a dome or a tongue-like coulée. It may extrude through a pre-existing solidified dome structure. Small initial explosions commonly accompany eruption onset, and dome growth may produce dome-collapse nuées ardentes. Based on his limited observations, Kemmerling (1921) expected nuées from dome collapse to remain small. However, events since the 1920s have proved that moderate-sized nuées, with relatively long runouts, sometimes occur with this class of activity. Because of the low gas pressure of the magma, large explosive outbursts do not occur. Examples of periods of class A activity at Merapi include 1883–1885, 1909–1918, 1939–1941 (Hartmann, 1935a; Van Bemmelen, 1949), and perhaps 1992–1993.

Class B activity is associated with magma higher in gas content. As it rises in the vent, relatively small explosions blow out the material plugging the orifice, allowing viscous magma to flow out. Because new magma presumably is more gas-rich than class A magma (there are little data on gas content; see Hammer et al., 2000 – this volume), subsequent, more energetic explosions can produce fountain-collapse nuées artentes. These small vulcanian eruptions can destroy parts of the dome or edifice, and dome-collapse nuées are not precluded and can occur, especially in the final phase when a viscous gas-poor lava effuses from the vent. Thus, ultimately, two types of nuées ardentes may form, and the order of occurrence can vary. The small initial explosions marking the beginning of this eruptive activity (Hartmann's fore-phase) can perhaps provide warning and allow time for evacuation and other mitigation measures before onset of the more destructive phase. Examples of periods of time when class B activity has occurred at Merapi include 1862–1869, 1887–1889, 1891–1894, 1902–1908, 1920–1922 (Hartmann, 1935a); also, 1942–1945, 1953–1956, 1961, 1967–1969, 1972–1974, 1976–1979, 1980–1984, 1994–1998. The activity of 1930–1931 is commonly listed as class B by Hartmann, but events of this period were complex and partly atypical of this class (see description below for 1930–1931, in *Historical eruptive activity*).

Class C activity involves a moderately gas-rich magma, which causes explosions large enough to pulverize the magma into a full range of possible sizes with (Hartmann assumed) no initial small explosions to serve as a warning of possible larger explosions. Thus class C eruptions are inherently more dangerous. The summit is usually partially destroyed, forming a new explosion crater, with the duration of the explosions generally brief. Fountain-collapse nuées ardentes are formed. After the explosions, the degassed magma commonly forms a lava dome or tongue. Examples of periods of time where class C activity has been reported at Merapi include 1832–1836, 1837–1838, 1846–1847, possibly 1878 and 1879, 1897, and 1933–1935 (Hartmann, 1935a). Van Bemmelen (1949) also noted that 1897, and possibly 1878 and 1879, belong to this category, but we suggest that these events, and also 1837–1938, might better be graded as B activity. In a number of cases, the distinction between B and C activity seems poorly defined, and thus we suspect that some of the events previously listed as C might deserve a lower rank. A main distinction with class B appears to be its high explosivity near the onset of activity. As a generalization, fountain-collapse nuées ardentes of class C should be volumetrically larger and affect larger areas than those of class B, although Hartmann appeared to emphasize the several successive phases of activity comprising an eruption, and not just size. In our view, class C climax eruptions can generally be thought of as moderate to moderately large vulcanian explosions (VEI 2–3), and those of class B as small to moderate vulcanian explosions (VEI 1–2).

Class D represents the eruption of a highly gas-saturated magma, usually initiating with fountain-collapse nuée activity that clears the upper part of the orifice. The escaping gases ream the vent, and lower the fragmentation surface on the depressurized magma column, leading to a culminating "intermediate gas phase". Eruptions of this class commonly destroy the top of the volcano, and are accompanied by abundant and voluminous nuées ardentes, as in 1849 and 1872. Vent collapse can follow the "main phase". An "after-phase" can occur with effusion of gas-poor viscous magma as in 1822–1823. We presume the eruption style at climax to be moderately large to large vulcanian to sub-plinian (VEI 3–4, and more rarely VEI 5). This is the most dangerous class of activity at Merapi.

The apparent presence or absence of fore-phase activity and the apparent "suddenness" of explosive volcanism depends largely on the intensity of monitoring and visual observations. Effective monitoring is only a relatively recent activity at Merapi. Whether or not an eruption onset appears to be sudden or not depends upon the available and possibly limited information, and partly for this reason we suspect that some eruptions may have been incorrectly graded. Thus, the assignment of the Hartmann rankings must be considered qualitatively, especially for the nineteenth and early twentieth century activity, before systematic modern monitoring. (Similar limitations also apply to VEI rankings). Where such uncertainty exists the rating in our text is qualified by a question-mark. The eruption volumes are poorly known, so this criterion is generally not helpful. In some cases, column height is reported and may be useful as one criterion for classification, but one should recognize that some fountain-collapse eruptions can be sizable and yet have limited column height, and that co-ignimbrite plumes can rise to appreciable heights without having a direct relation to processes at the summit crater.

Finally, to place Hartmann's classification in a more modern context, the gas contents referred to above are for magma high in the conduit or vent, nearly at the surface. Recent eruptions including Mount St. Helens, Unzen and Montserrat have shown clearly that explosivity is a function of the balance between gas supply to the near-surface, and the rate at which it is bled off through a permeable system (Eichelberger et al., 1986; Jaupart and Allegre, 1991). Gases in viscous but fast-rising magmas cannot escape rapidly enough so that explosions may ensue, and in addition, eruption precursors can develop over a short period (C. Newhall, written communication). In some cases Merapi magmas rise more slowly or de-gas more effectively than others, to produce Hartmann A/B eruptions. Few hard data exist at Merapi to enable specific correlations of explosivity to ascent rate of magma (see Hammer et al., 2000 – this volume), but it is probably helpful to consider the Hartmann scheme in this context.

3. Historical eruptive activity

A chronologic narrative of historical activity at Merapi is given below. The gaps between dates should be interpreted with caution, for Merapi has been so frequently active that few instances of true dormancy are firmly documented. Even during periods where no effusive or eruptive activity is recorded, the volcano could have been active with undetected (or unreported) low-rate dome growth, or earthquakes, rock avalanches, gas emissions, and small steam explosions that could have been precursors for subsequent larger events. The periods reported have been divided for convenience of description, and are not necessarily "cycles" in the formal sense proposed by Hartmann.

The descriptions below begin with 1768. Several accounts of Merapi historical activity also include a supposed eruption in 1006 AD, but there is no convincing evidence for this event—the inference is based on a misreading of old chronicles (Newhall et al., 2000 – this volume). Franz Wilhelm Junghuhn (1853–1854) has discussed some other early eruptions, including those of 1560, 1664, 1678, 1768, and others up to 1846–1847 (see also, other Junghuhn publications and additional early references cited by Hartmann (1935a)). The severe eruption of 1664 was also described by Crawfurd (1820, p. 509). In the accounts below, only the key references are cited but additional literature is mentioned in these sources. VEI values ≥1 are generally noted. VEI 2 is a default value used in the Smithsonian compilation, but in many cases we have reduced the ranking to VEI 1. The reader should note that VEI rankings can be applied to individual eruptions whereas the Hartmann classes may refer to a sequence of events, often lasting several years. An abbreviated chronology is also given as a tabular summary (Table 2).

1768: An eruption was accompanied by a lava flow and lava "avalanches" (rockfalls) according to Junghuhn (Neumann van Padang, 1983). Dome growth was also mentioned by Kemmerling (1921). Hartmann A?; VEI 2?

1786: F.v. Boekhold (1792) ascended the summit (possibly the first European to do so) and reported trees around the crater wall, suggesting recent (<18 years) inactivity (Neumann van Padang, 1983). Barren rock ("kale klip") was described, evidently a lava dome, with "burning sulfur" (Kemmerling, 1921). Hartmann (1935a) shows a schematic profile for this year (Fig. 3). Hartmann A?; VEI 1?

1791: By this date a large crater-forming explosion had occurred, followed by growth of a lava dome (Figs. 3 and 4; Hartmann, 1935a). The dome extended to the south, southwest and west parts of the crater.

Table 2
Merapi activity and nature of eruptions from 1768–1998 [Symbols are as follows: X, explosion; Xp, explosion that caused ashfall; E, undifferentiated eruption; L, lava flow; Dg, dome growth; Dd, dome destruction (partial destruction, unless otherwise noted in the “comments” section); N, undifferentiated nuée ardente; Nd, dome-collapse (Merapi-type) nuée ardente; Nf, fountain-collapse (St. Vincent-type) nuée ardente; G, significant gas emission during non-eruptive events; ?, uncertainty; (), possible]

Year	Class	Activity	Remarks	V.E.I.	Ref.
1768	A?	E, L, Dg		2?	Junghuhn (1853–1854); Neumann van Padang (1983); Kemmerling (1921)
1786	A?	Dg		1?	Kemmerling (1921); Neumann van Padang (1983)
1791	C?	X, Dg	> 100-m crater was result of eruption after 1786; no good description.	2	Junghuhn (1853–1854); Hartmann (1935a)
1797	A	Dg		1	Hartmann (1935a)
1807	A?	X	Gas explosions but no effusive activity.	1?	Hartmann (1935a)
1810	A?	Dg		1	Hartmann (1935a)
1812–1821	A?	Dg		1	Hartmann (1935a)
1822–1823	D	E, X, Nf, Dg, L	Explosive destruction of lava dome, 600-m circular crater. Violent Nf in several sectors. 8 villages destroyed.	3 (4)	Junghuhn (1853–1854); Kemmerling (1921); Hartmann (1935a); Van Dijk (1876)
1832–1836	B?(C)	X, Nf?, Nd, L, Dg, Dd, Nd	Described as violent explosion, “sudden and unexpected” but 300 m × 150 m horseshoe-shaped crater suggests mainly dome collapse.	2? (3)	Junghuhn (1853–1854); Hartmann (1935a); Kemmerling (1921)
1837–1838	B?	X, Nf?, Nd, L, Dd, Dg	New dome growth after destruction of the old dome. Crater smaller than 1932.	2?	Junghuhn (1853–1854); Hartmann (1935a); Neumann van Padang (1983)
1840	A	E, X?	“Heightened activity after earthquake.”	1	Hartmann (1935a)
1846–1848	C	Xp, Nf, Nd, Dd	Dome destroyed 200 m × 150 m elliptic crater. Initial Nf. Nd to S (Woro, Gendol).	3	Junghuhn (1853–1854); Kemmerling (1921); Hartmann (1935a)
1849	C (D)	E, Xp, Dd, Nf? Nd probable	Strong X outbreak, gas phase. 3 cm lapilli to 18 km. Dome destroyed, Nd? To SW. S, E, N sectors spared. 400 m × 250 m Horseshoe crater suggests role for Nd.	3	Junghuhn (1853–1854); Kemmerling (1921); Hartmann (1935a)
1861	(B)	X, G	Lava “plug” in crater totally destroyed by explosion.	(2)	Anonymous (1886); Kemmerling (1921)
1862–1864	B	L, X, Nd, Dg	Lava filled 1849 crater. Nd to W.	2	Anonymous (1864); Hartmann (1935a)
1865–1871	B	X, Dd, Dg, L, Nd	Intense gas-rich effusion then explosion, with horseshoe crater 300 m × 250 m open to W. Lava breakout to Blongkeng.	2	Anonymous (1867); Kemmerling (1921); Hartmann (1934a, 1935a)
1872–1873	D	Xp, Dd, Nf	Dome destroyed violent eruption 600 m × 480 m oval crater, 500 m deep. Nf mainly W and S (Blongkeng, Woro, Gendol).	4	Kemmerling (1921); Anonymous (1873); Hartmann (1934a)

Table 2 (*continued*)

Year	Class	Activity	Remarks	V.E.I.	Ref.
1878–1880	B	Xp	Two explosive eruptions.	2	Hartmann (1934a); Neumann van Padang (1936)
1883–1884	A	Dg	Effusive dome growth continued until May 1884. Small steam X.	1	Neumann van Padang (1933, 1936); Anonymous (1885)
1885–1887	A	X, Dg	Small steam explosions and rock avalanches not related to dome growth occurred.	1	Anonymous (1885); Neumann van Padang (1936)
1888	B	Xp, Dg, Nd, L	Dome growth, destroyed on W, series of strong Nd to 7.5 km to W; Trising, Senowo, Blongkeng	2	Anonymous (1890); Neumann van Padang (1936); Kemmerling (1921)
1889	A	X, G	Small steam explosions and gas emission occurred.	1	Anonymous (1891)
1891–1894	B?	Xp, Dg	Small collapses accompanied dome growth. Lava bombs? tephra.	2?	Anonymous (1893); Kemmerling (1921)
1897	B?	Xp, G	Small steam explosions, gas emission. Lava bombs?	2?	Anonymous (1898); Kemmerling (1921)
1902–1904	B	G, Dg, X, Xp, L, Nd, E	Fumarolic activity, Dg end 1902. 1903 earthquake increase activity East Dome. Woro breach E. peak January 1904 Nuées to E. 16 deaths.	2	Hartmann (1934b); Anonymous (1904b, 1905); Kemmerling (1921)
1905–1906	B	Xp, E, L, Dg, N	E, Nuée in January 1905; L, Woro. 1906, E Woro, then lava. Nd.	2	Hartmann (1934b); Anonymous (1908)
1907–1908	A	Xp, Dg	Minor ash. Near quiescence. Dg in 1908.	1	Anonymous (1909); Wurth (1914)
1909–1913	A	X, Dg, Nd	Activity to NW. Nd. E-Dome through 1911, then W-dome.	1	Wurth (1914); Kemmerling (1921)
1915	A	E, Dg	New cycle began; minor destructive phase, Dg.	1	Kemmerling (1921)
1920–1923	B	X, Dg, Nd	X begins cycle. Dg, Nd causes 35 deaths. First scientific Nd observations at Merapi. Continued Dg through 1923.	2	Kemmerling (1921); Anonymous (1921, 1923, 1924); Neumann van Padang (1933)
1924	A	G, X, N	Gas emission, temp rise, seismicity, rock avalanches.	0	Anonymous (1925); Taverne (1925)
1925–1929		Quiescence	Long period of dormancy.		Purbo and Suryo (1980)
1930–1931	B	L, Nd, (X), Dg	L effusion undermines dome complex; series Nd/debris avalanches to 12 km; horseshoe crater. 1369 deaths.	3	Kemmerling (1931); Neumann van Padang (1931, 1933); Escher (1933a); Grandjean (1931a–c)
1933–1934	C	Xp, Nf, Dg, Nd	Series of X vulcanian, Nf. Plume $<$1 km. Nd in 1934 to 7 km.	2	BNEIVS, no. 61–70; Hartmann (1935b)
1935–1939		Quiescence	Small sporadic rock avalanches.		BNEIVS, no. 71–86.
1939–1941	A	Xp, Nf, Dg, Nd	Effusion February 1940 preceded by X, pit 100 m diam. Plumes to 3 km, Nf.	2	BNEIVS, no. 95–98; Van Bemmelen (1949)
1942–1945	B	Xp, Nf, Dg, Nd	Initial X phase similar to previous cycle. Dg with energetic Nd, some X.	2	Van Bemmelen (1949); BNEIVS, no. 95–98; Petroeschevsky (1953)
1948	A	X, Dg, L	Explosion marks new effusive cycle, rockfalls.	2	Petroeschevsky (1953)

Table 2 (*continued*)

Year	Class	Activity	Remarks	V.E.I.	Ref.
1949–1952		No activity recorded.			Purbo and Suryo (1980)
1953–1956	B	Xp, Dg, Nd, Nf?, L	Initial X. Large N in 1954; DRE vol deposits > dome vol. 64 deaths.	2	BVSI, no. 100
1957–1959	A	E, L, Nd, Dg	Lava effusion, some Nd.	1	BVSI, nos. 101–102; Purbo and Suryo (1980)
1961	B	Dg, Xp, Nd, Nf?	Dg, Nd to 7 km. Paroxysm 8 May, 30 min. Nuées to 12 km. Deposit vol 20×10^6 m^3. 6 deaths.	3	BVSI, no. 104
1962–1966		Quiescence	Destructive lahars, 1962. No effusion. Minor activity 1966.		BVSI, nos. 104, 106.
1967–1969	B	E, Dg, Nd, Nf?	Vent-clearing X incandescent Dg, rockfalls, parox October 7–9, destroy 1967 lava, nuées to 7 km. January 1969 paroxysm, nuées of unknown type to 13 km to W.	2	BVSI, no. 106; Shimozuru et al. (1969); Siswowidjoyo (1984)
1970–1971		Quiescence	Sporadic rock avalanches.		BVSI, no. 106
1972–1974	B	Xp, Dg, Nf, Nd	October 1972 X, new cycle. Nf to 3 km, small crater. Similar X to February, Slow effusion to February, September Nd to 6 km, December Nf to 7 km. Lahars.	2	Siswowidjoyo and Harjowarsito (1974); Siswowidjoyo (1984)
1976–1979	B	X, Dg, Nd, Nf, Dg	Dome building, Nd to 6 km; Dg through 1977. January 1978, partial collapse by X; new Dg, lava tongue.	2	Siswowidjoyo (1984)
1980–1984	B	Dg, L, Nd, Xd, Nf?	Dg May, 60% collapse December 1980, Nd. November 1982 Nd to 8.4 km. Dec, new lava, X 15 June 1984, nuées to 7 km W. Plume to 6 km.	2	Siswowidjoyo (1984); Ratdomopurbo and Poupinet (2000); SEAN (1989)
1984–1991	A	Dg, Nd	Waning Dg. October 1986 Nd, no precursors. Dg waned, after 1887 only upper part. 1990 gas burst. Accel seismic, deformation.	2	Ratdomopurbo and Poupinet (2000); Young et al. (2000)
1992–1993	A	Dg, Nd	Breakout January 1992, Nd to 4.5 km on NW. Crater rim overtopped by lava on N. Other brief Nd episodes.	2	Ratdomopurbo and Poupinet (2000); Young et al. (2000)
1994–1998	B	Dg, Nd, X, Nf	Resurgent Dg, Nd to SW and S, 6.5 km. No precursors. Dg resumed, minor Nd 1996. X January 1997, Nf to 6 km. July 1998 Nd to 7 km to SW. Tilt, seismic alert.	2	Voight et al. (2000); Abdurachman et al. (2000)

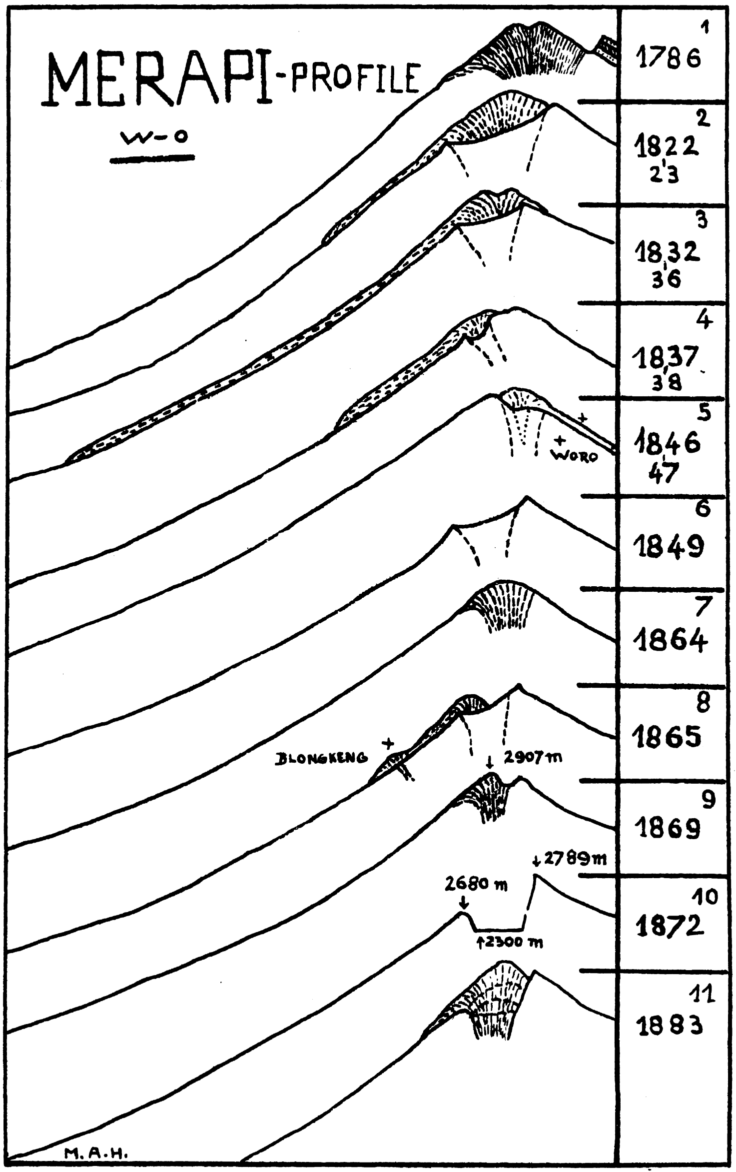


Fig. 3. Original schematic west-to-east profiles through Merapi Volcano, 1786–1883 (Hartmann, 1935a). Superscript numbers in the boxes refer to the number of the profile and have nothing to do with the year cited. Local breaches of the crater are indicated by " + " symbols.

The 100–130-m-wide crater, near Pasarbubar (cf. Fig. 8), was caused by an eruption since 1786 but no description was recorded. Hartmann C?; VEI 2.

1797: Dome growth in the pre-1791 crater was reported for this year by Dechamps, cited in Hartmann (1935a). Hartmann A; VEI 1.

1807: Explosive activity possibly took place this year (Hartmann, 1935a), but no effusive activity was mentioned. Hartmann A? VEI 1?

1810: Dome growth occurred (began?) this year; (Hartmann, 1935a) cites Horsfield. Hartmann A?; VEI 1.

1812–1821: Dome growth continued and ended in 1822 before the eruption of that year. Hartmann

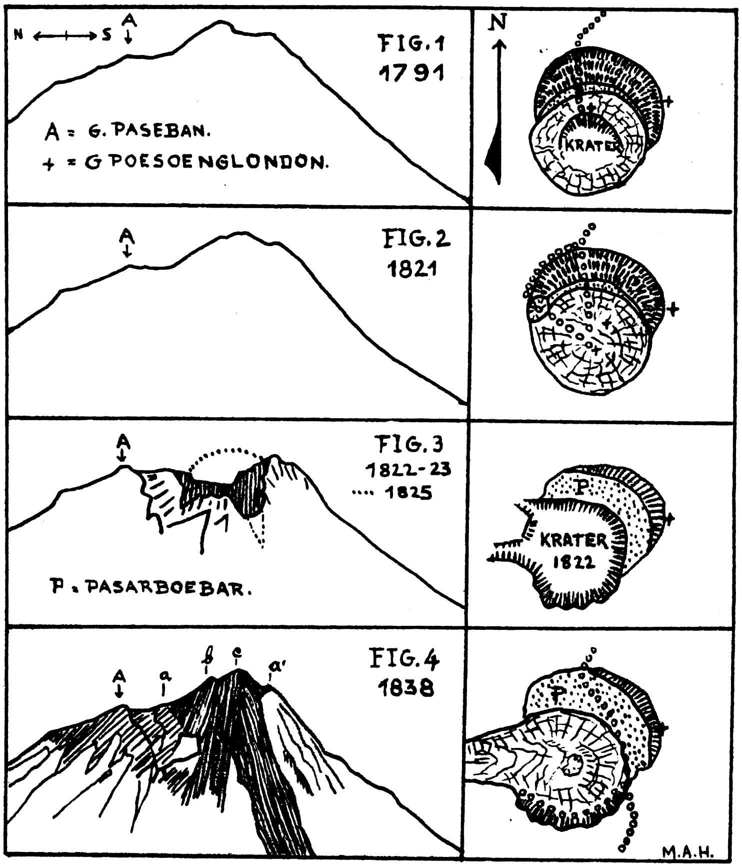


Fig. 4. Original profiles and sketch-maps of the Merapi summit, 1791–1838 (Hartmann, 1935a). *A* is location of Paseban, " + " is location of Poesoenglondon; other lower case letters are points referred to by Hartmann.

(1935a) provides a description and sketch of the 1821 summit (Fig. 4). Hartmann A?; VEI 1.

1822–1823: "The eruption took place quite unexpectedly during a swarm of violent earthquakes of long duration, felt in various villages in central Java around 9 p.m., 27 December, developing into a paroxysm on 29 and 30 December" (Hartmann, 1935a, citing Junghuhn and others). Shocks "repeated 18 times in 30 hours…some were very severe and frightening… At the same time, roaring was heard from Merapi and it began to throw out rocks… On the morning of the 29th there was an eruption with half the mountain surrounded by fire columns, while a thick rain of sand and small rocks fell on surrounding fields… In the afternoon, shaking was stronger, and a new less-severe eruption developed, lasting an hour… On the 30th violent shaking was again felt and somewhat later a new eruption was heard… At midnight the most severe shaking, which lasted a quarter hour, terrified people; they hastened outside and a column of fire was seen ascending on the southeast" (Van Dijk, 1876). Violent explosions destroyed the dome west of the summit, and "the mountain became covered by firestreams" (Kemmerling, 1921). The most violent activity occurred on the west and southwest, but ravines on the north were also filled by hot debris. Lapilli and ash fell as far as Bojolali (Boyolali), Muntilan, Magelang, and Yogyakarta (Fig. 2).

A crater of about 600 m in diameter was created (cf. Figs. 3 and 4; Hartmann, 1935a), with breaches in directions of the Apu, Blongkeng, and Woro rivers (Figs. 1 and 2). Debris accumulated near Pasarbubar (Fig. 8). Nuées ardentes descended the Gandul, Apu, Lamat, Blongkeng, Batang, Gendol, and Woro rivers.

Eight days of abundant rains then unleashed hot lahars, with overbank lahars "streaming through fields adjacent" to river courses. On the Batang at 20 km Junghuhn reported lahar deposits so hot that men could not cross 9 days later. The explosions lasted until 10 January 1823. This eruptive period claimed 50 lives by nuées and a like number from lahars; eight villages were destroyed (Hartmann, 1935a; Kemmerling, 1921). Hartmann D, VEI 3 or (4).

By mid-January a new lava dome began to form in the crater with a short lava tongue toward the Blongkeng (Fig. 4; Hartmann, 1934a; Anonymous, 1908).

1832–1836: Activity began "suddenly and unexpectedly at midnight" on 25 December 1832 and ended in 1935 (Van Dijk, 1876; Kemmerling, 1921; Hartmann, 1935a). At the beginning of the eruption, a violent explosion partially destroyed the western portion of the dome of 1823 and a part of the top of the lava flow (Fig. 3). A large dome collapse occurred with over half of the material transported towards the west by a nuée ardente; tephra covered Pasarbubar. Nuées ardentes invaded the Blongkeng and Lamat valleys, and 32 were killed. Hartmann B or C?; VEI 2 or 3.

A small crater formed and new lava filled it as in 1822. Many earthquakes occurred during the eruptive phase and may have triggered dome-collapse nuées ardentes (Kemmerling, 1921).

1837–1838: A period of activity similar to that of 1832–1836 began "suddenly" (Hartmann, 1935a) with an explosion on 10 August that partially destroyed the lavas of 1832–1836 and opened a new crater (Figs. 3 and 4). Nuées ardentes descended the Blongkeng. Hartmann B?; VEI 2?. An effusive phase followed and in 1838 the eruption ended with a summit morphology more or less similar to that of 1836 (Fig. 3; Junghuhn, 1853; Hartmann, 1935a; Neumann van Padang, 1983).

1840: "After the earthquake of 4 January 1840, heightened volcanic activity was observed" (Hartmann, 1935a). Similarly, Van Dijk (1876) reports "multiple shocks at various locations…Merapi seemed to smoke more strongly than usual after this incident." Hartmann A; VEI 1.

1846–1848: "The explosive eruption occurred on the night of 1–2 September 1846, whereby flames and mainly black ash clouds were ejected from the summit" (Hartmann, 1935a, citing others). The "sudden" explosion was followed by a series of other explosions, opening a crater of ~200 m diameter to the east and southeast of the summit (Fig. 3). Nuées descended the Woro and Gendol valleys. Hartmann C, VEI 3. The first phase was of great explosivity due to the "gas-rich magma," leading to south-directed "nuées ardentes of the St. Vincent type" (Hartmann, 1935a). After the second phase of small explosions, lava filled the crater. The rainy season produced hot lahars, and the eruption probably ended October 1847, although some "explosion"-like sounds (rockfalls?) were noted on 8 January 1848. Fig. 3 shows the location of Woro and Blongkeng breaches by " + " symbols.

1849: On 26 April a strong, vertical explosion was accompanied by fountain-collapse nuées ardentes. No further activity occurred until 14–15 September, when a series of strong explosions destroyed the west part of the summit and dome (Hartmann, 1935a). Fountain-collapse nuées (?), and/or dome-collapse nuées, ran down the Blongkeng. On 24 September another explosion ended this destructive phase, and no effusive phase followed. The crater was $400 \times 250\ m^2$ in diameter and 250 m in depth, but horse-shoe shaped, suggesting dome collapse may have occurred (Fig. 3). Likewise, the south, east and north were spared of the danger, and this seems unlikely as an outcome of a large fountain-collapse eruption unless the horseshoe-shaped feature were present before the explosion fountain developed. The explosions resulted in fallout of 3-cm clasts in Muntilan (18 km) and 1-cm lapilli in Magelang (25 km) (see Fig. 1). About 800 houses and 500,000 coffee trees were destroyed, suggesting "that the ash eruption was certainly important" (Kemmerling, 1921), and Yogyakarta and Solo were buried by "one Dutch inch" of ash. Hartmann ranked the eruption as D. We wonder whether the crater size reported may be possibly due mainly to dome collapse, a form consistent with debris distribution in only one sector; if so, we suggest the ranking might be Hartmann C; VEI 3.

1861: An explosion reported in this year destroyed the plug of lava (Anonymous, 1886; Kemmerling, 1921). Hartmann (B); VEI (2).

1862–1864: On 26 May 1862 lava opened a vent in the 1849 crater and filled it by 1863. In July 1863, "a heavy smoke column, now and then mixed with flames and sparks, rose upwards from the crater" accompanied by felt seismicity (Anonymous, 1864). Activity increased after 23 July, and on the 28th "the mountain was set entirely ablaze… Fire arose from 3 craters simultaneously" southeast of the summit. Lava dome growth resumed and continued until 1864 (Fig. 3). Glowing rockfalls and small nuées ardentes occurred from the dome (Anonymous, 1864; Hartmann, 1935a). Hartmann B; VEI 2.

1865–1871: Seismicity was noted in October 1865 and interpreted as an eruption precursor: "There seems to be a more or less violent eruption of Merapi drawing near again, insofar as one might suppose this from the manifestations observed here (Kadu) the last few days" (Anonymous, 1867). New explosive activity began in October, and from a point near the Blongkeng "The roaring was horrifying…one saw masses of rock sliding down in great quantities, without interruption…the noise was growing more violent, and a moment later the densest mass of ash, like thick clouds of dust, was seen having the shape of a wooly, curling and weltering colossus, sliding downslope… The speed must have been enormous… The rain of ash about us was severe, and the brown faces of the Javanese accompanying us were speedily colored white!" In November, "smoke" columns were observed, sometimes with "fire," and ash falls were reported (Anonymous, 1867). By late November, activity had diminished and inhabitants returned to the higher mountain communities and found their plantings destroyed.

Hartmann's sketch for 1865 (Fig. 3) shows a crater and partial filling by a new dome, suggesting the events included destruction of the old dome and effusion of new lava. Verbeek and Fennema (1896) reporteded complete destruction of the dome in 1865, with a crater open to the west (Hartmann, 1934a). An observer in January 1866 reported lava at least 200 m high in the Blongkeng cleft "of hemispherical shape, apparently pierced by a crater opening" (Anonymous, 1867). The lava advanced until 1867 (Kemmerling, 1921).

The artist Raden Saleh painted two pictures of Merapi during the eruption of 1865 (Fig. 5), one showing the volcano by day, and the other by night. Kemmerling found that the paintings were done from G. Plawangan on the south flank (Escher, 1933b). These paintings display incandescent "lava-block" rockfalls (*Guguran*), typical of Merapi eruptions, descending a broad swath across the south and west flank. Hartmann B; VEI 2.

From 1867 through 1871 dome growth persisted (Anonymous, 1867; Kemmerling, 1921). In May 1869, a new surge of lava was directed toward the Blongkeng (a high-altitude vent is shown in Fig. 3, part 8; Hartmann, 1935a), with nuées ardentes and ashfalls, prompting spontaneous evacuations by inhabitants of higher villages. In August 1871, a lava dome 250 m high rose above the Pasarbubar surface, with the top at 2890 m incised by a 50-m deep sickle-shaped crater (Figs. 6 and 7), and a smaller dome projecting above the rim (Hartmann, 1934a). The dome grew to 2907 m and overflowed the west rim; the remaining crater was 250 m broad and 50 m deep. This dome then remained stable and no nuées were reported in 1869; dome growth persisted at a low rate (Hartmann, 1934a).

1872–1873: The dome was completely destroyed soon after 15 April 1872, the onset of a great explosive eruption that lasted 5 days (Kemmerling, 1921; Hartmann, 1934a; 1935a and the author's references). "The eruption began unexpectedly quickly with a violent explosion…" The early phase occurred 15–17 April, the paroxysm April 17–20, ending April 20 "as suddenly as it had begun, after an uninterrupted duration of 120 hours" (Hartmann, 1934a). Further, "detonations were compared with violent cannonade,…and observed west as far as Krawang and Preanger, and east as far as Madura and Bawean island." The profile and map sketches for 1872 (Figs. 4, 6–8, 10) illustrate the open crater, estimated by Verbeek in 1883 as $480 \times 600\ m^2$ (Neumann van Padang, 1936). Nuées ardentes and tephra fall caused by the explosion destroyed all villages above 1000 m elevation. Hartmann D; VEI 4.

Fountain-collapse nuées flowed radially from the vent and ravaged the Apu, Trising, Senowo, Blongkeng, Batang, Woro and Gendol drainages (Figs. 1 and 2). The eruption occurred "suddenly" with no preliminary phase detected (Kemmerling, 1921). This feature of sudden onset with few or no precursors was assumed by Hartmann as characteristic of class D eruptions. The large crater of Mesdjidanlama was created, with breaches at Blongkeng, Woro, and Gendol sectors (Fig. 6). The map also shows the former lava dome and 1871 crater, with a location

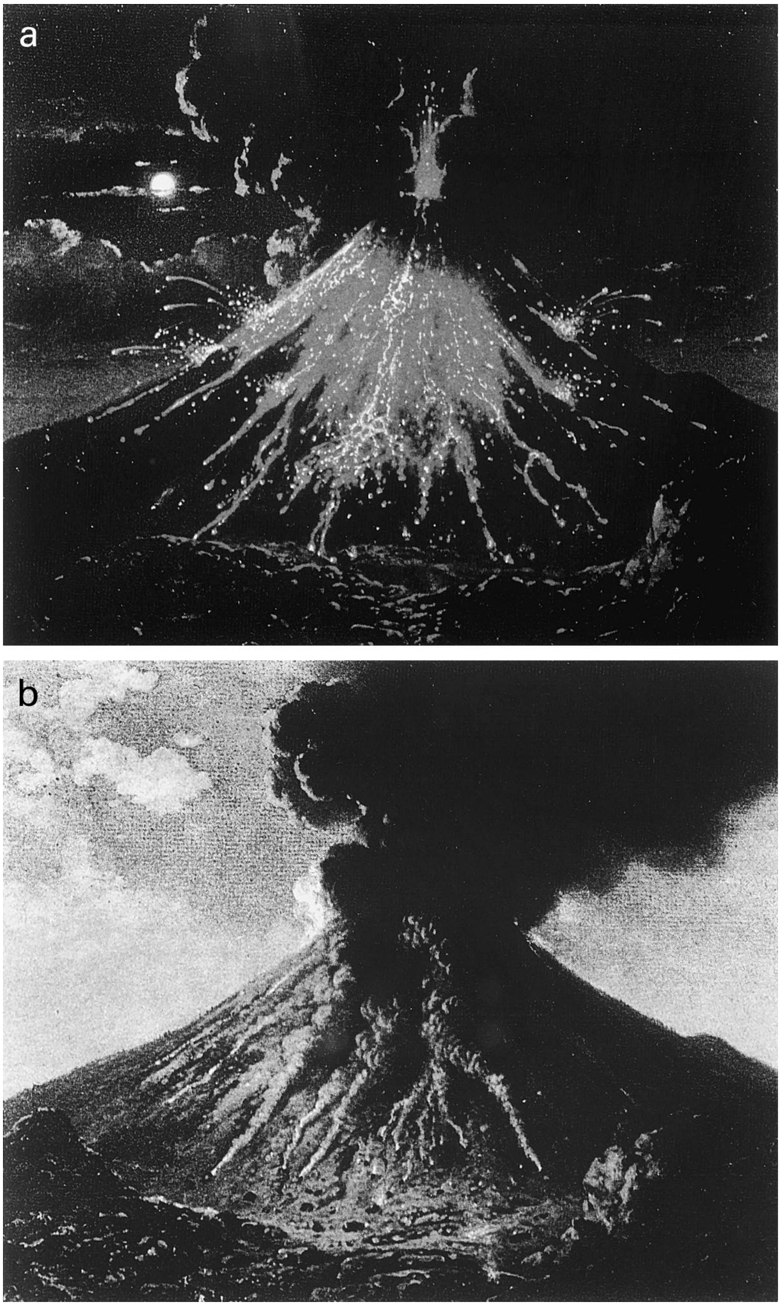


Fig. 5. Merapi eruption of 1865. Paintings by Raden Saleh showing the volcano by night (a) and by day (b) (Neumann van Padang, 1983). The original paintings are discussed by Escher (1933b).

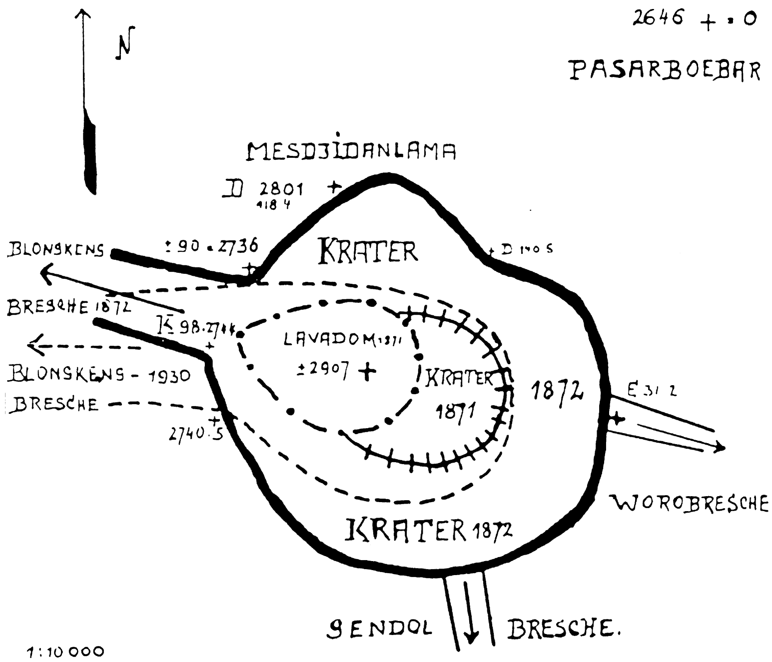


Fig. 6. Original sketch-map of Merapi summit before and after the eruption of 1872 (Hartmann, 1934a). Crater of 1871 (cross-hatch line, after Blij); lava dome of 1871 (dash-dot line, after Blij); crater rim of 1872 (heavy solid line, after Verbeek); breaches at Gendol, Woro, and Blongkeng. Positions of Mesdjidanlama and G. Pasarboebar shown for reference (cf. Figs. 8 and 9). The crater of 1930 (dashed line, after Neumann) shown for comparison.

that coincides with the 1930 crater and thus indicates a relatively long-lived conduit locus. On 3 and 4 November , new explosions resulted in ashfall in surrounding areas. From November 1872 to early 1873, Merapi was active but not all events were recorded (Anonymous, 1873; Hartmann, 1934a; Kemmerling, 1921).

1878–1879: In each year a small eruption occurred and ejected blocks that fell in the 1872 crater and filled it to 2640 m (Hartmann, 1935a). Hartmann classified this as C, but B seems more appropriate; VEI 2.

1883–1884: Beginning in December 1883 a new dome emerged in the crater of 1872, with growth continuing to May 1884 (Anonymous, 1885; Stoop, 1885; Kemmerling, 1921; Neumann van Padang, 1934, 1936 (especially), 1937; Hartmann, 1935a). The crater shape is known from Verbeek in 1883, with details confirmed by Neumann van Padang (1936). Part of the 1883 crater floor was identified by him in the wall of the 1930 crater. As for the new dome (Figs. 9 and 10), Verbeek wrote in January 1884 (quoted in Neumann van Padang, 1936), “In the

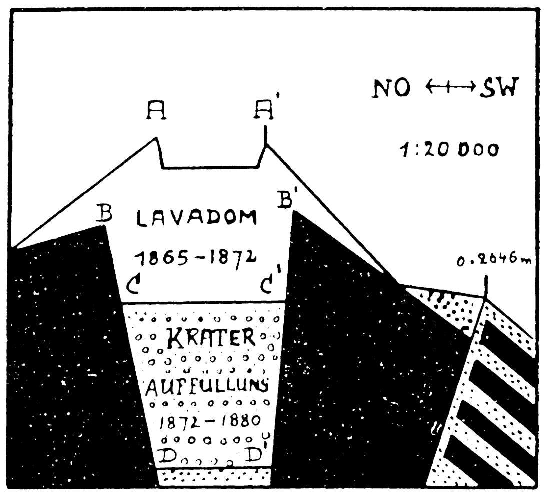


Fig. 7. Original cross section of Merapi summit showing former lava dome of 1865–1872 and crater $A–A'$ (unshaded) that was destroyed in the eruption of 1872 (Hartmann, 1934a). Crater partly refilled with lava $C–C'$, 1872–1880. Southwest (on left) to northeast view (erroneously marked on figure). On right are bedded lavas on the old crater rim, under Poesoenglondon (cf. Fig. 8).

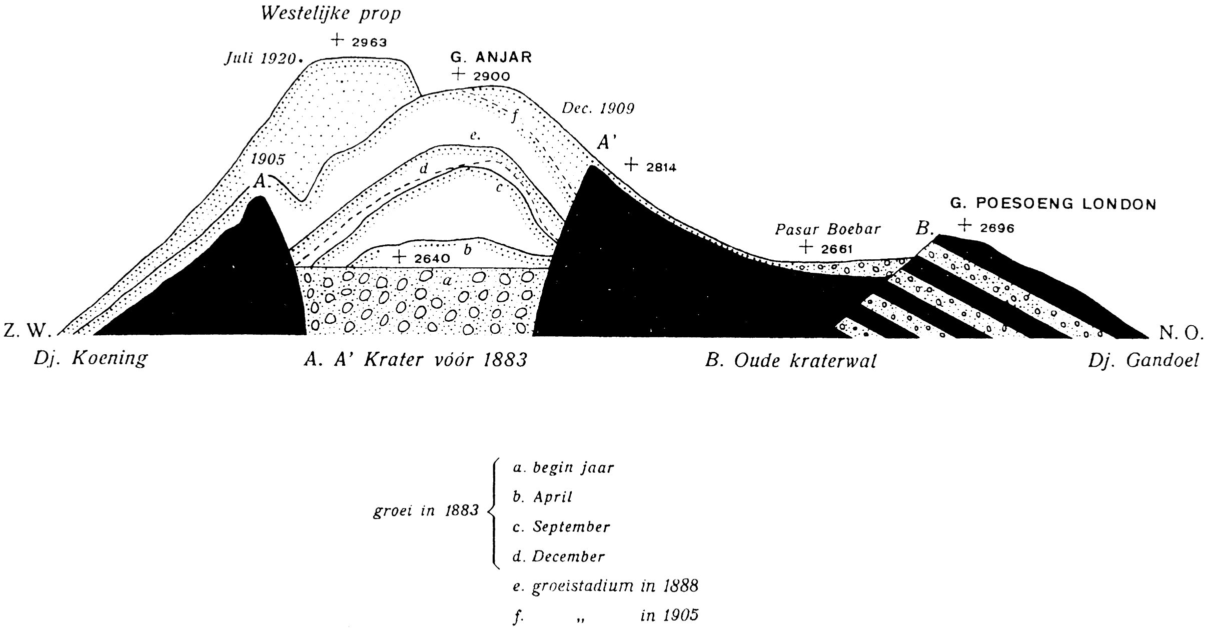


Fig. 8. Original cross section through Merapi summit showing lava dome growth in 1872 crater *A*–*A*′, beginning approximately from 1883 (cf., Fig. 7) as shown by infill pattern within crater (Kemmerling, 1921). Various G. Anjar ("East Dome") lava growth stages after 1883 (noted by *a*–*d*), 1888 (by *e*), and 1905 (by *f*), with upper surface December 1909. "West Dome" (*Westelijke prop*) profile shown on left, for 1920. Pasarboebar and Poesoeng London ridge to northeast, marking the old crater wall (*B*). Flank sectors beyond the cross-section are the Koening (left, marked as southwest [but actually south]) and Gandoel (right, northeast) valleys. Cf. Fig. 9.

crater, surrounded by very steep nearly-perpendicular walls, a new cone was built, whose highest point at the end of December was one meter above the highest north part of the crater rim…; the deepest part lies 126 m under the north rim." Hartmann A; VEI 1. Further evolution of the dome to 1909 is shown in Figs. 8 and 11; Fig. 8 also shows another dome ("West Dome", that grew in 1911–1913) as it existed in 1920.

1885–1887: Small steam explosions and rockfalls were recorded in 1885 (Anonymous, 1885). The engineer Stoop visited the summit monthly and recorded observations. He recognised that high-elevation villages could be destroyed by tephra and recommended that some houses there be constructed to resist a rain of "stones" (Neumann van Padang, 1936). Minor dome growth occurred (Fig. 8, locally between *d* and *e*) and Stoop made repeated surveys of dome height. In April 1885, he noticed that growth had stopped and reasoned that the conduit was clogged and, therefore, dangerous. He suggested to "eliminate the dome and a piece of the crater wall with 10,000 kg of dynamite, whereby the lava flow would be sent in a given direction" (Neumann van Padang, 1936). Later in May, he established that the dome had subsided about 30 cm, and "then maintained with certainty that one could assume the inner pressure had diminished."

Steam explosions and rockfalls accompanied the minor dome growth during the 1886–1887 activity (Anonymous, 1886, 1887; Neumann van Padang, 1936). In May 1886 Stoop observed steam rising in puffs from the dome, and fumaroles were noted in four general locations. Hartmann A?; VEI 1. An 1886 photo shows Merapi from Selo on the north flank (Fig. 12a).

1888: Minor rockfalls and "smoking" had been observed since March, and incandescence at the summit was reported 18 August, followed days later by glowing lava-block rockfalls to the west (Fig. 8; Anonymous, 1890; Neumann van Padang, 1936). Summit observations noted "the lava dome completely glowing," and after 31 August nuées ardentes occurred, accompanied by occasional lightning. A

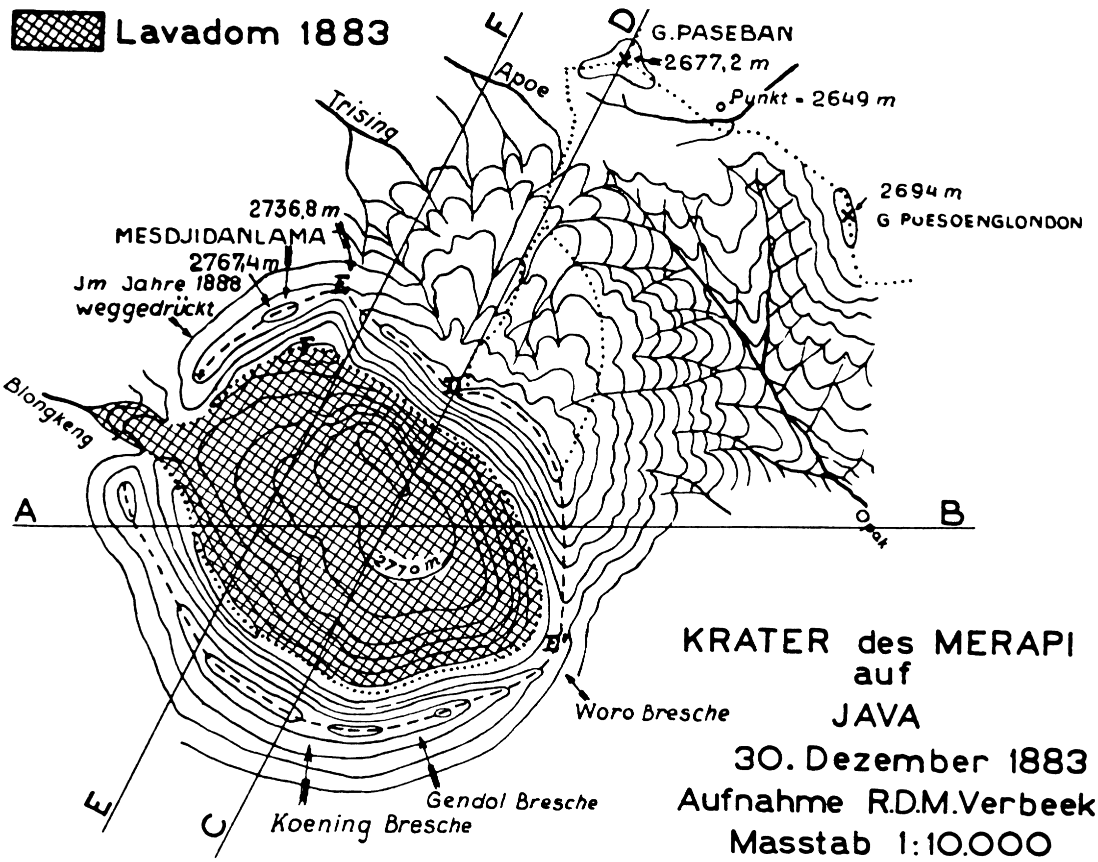


Fig. 9. Original sketch-map of Merapi summit showing lava dome of 1883 (cross-hatch pattern) inset in 1872 crater, based on information by Verbeek, December 1883 (Neumann van Padang, 1936). Cf. Fig. 8. Koening, Gendol, and Woro breaches are noted, as are topographic high points at Mesdjidanlama, Paseban, Poesoenglondon.

few burn injuries were reported and several villages between the Senowo river and Jrakah were partly abandoned and the cattle brought to safety. An eyewitness report is attributed to Mr. Hamming (in Anonymous, 1890): “The people had only sought shelter temporarily with their cattle, and were returning the next morning… The hamlet of Gendjikan was most endangered. The people had received the notice to move but did not want to… If a collapse unexpectedly occurs again like this one, which cannot be excluded, then I foresee the worst for these people.” The size of nuées grew in September, with those on 22 September descending 6 km on the Blongkeng and 7.5 km on the Senowo and Trising. The ladu (channeled block-and-ash flow) “followed the valleys a few km without destroying the villages along the banks… It is of great significance that the village Gendjikan on the edge of the Trising has not suffered and no people were killed, although the ladu debris mass travelled 2.5 km further west…” (Neumann van Padang, 1936). Hartmann B; VEI 2.

The dome was rebuilt, accompanied by occasional rockfalls, and activity diminished in November (Kemmerling, 1921). For the 1888 activity, Neumann van Padang recognized a fore-phase of over a month, the “main eruption” from 31 August to 22 September, and an after-phase of three months.

1889: Small steam explosions and gas emission were recorded for this year (Anonymous, 1891). Hartmann A; VEI 1.

1891–1894: Dome growth was accompanied by rockfalls. Explosions also took place, some of which

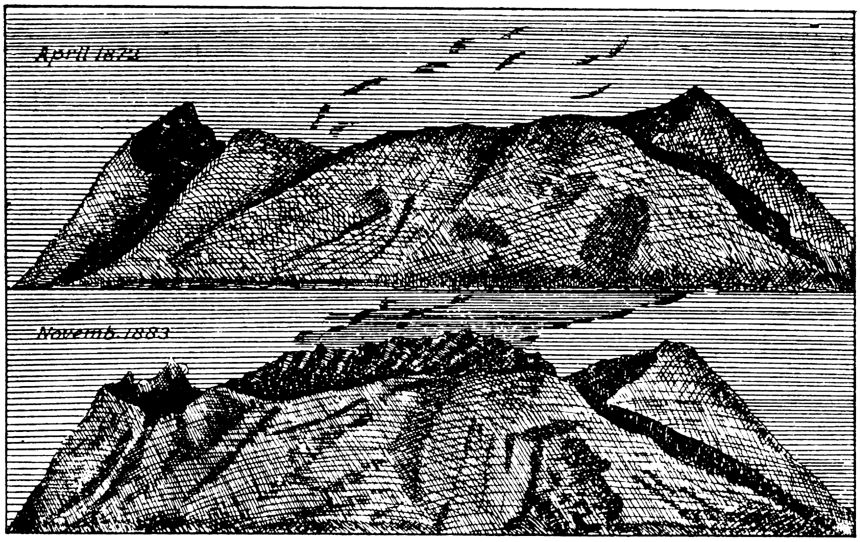


Fig. 10. Original sketches of Merapi summit in April 1872 and November 1883, based on information from H.E. Dorepaal. Viewed from the southwest from a point 30 km from the summit, and 10 km west of Djokjakarta (Fig. 2). The 1883 dome is inset into the crater of 1872 (Hartmann, 1934b).

produced ash fallout and lava bombs (1894) (Anonymous, 1893; Kemmerling, 1921). In August 1891, "dense smoke and fireglow on the northwest side" were noted, and in October 1894, incandescence at the summit and rockfall noise were reported by villagers. Merapi apparently was inactive in 1893. Hartmann B; VEI 2.

1897: Small explosions occurred, violent enough to throw lava bombs (Kemmerling, 1921), possibly those found in Pasarbubar. Gas emission was reported (Anonymous, 1898). Hartmann graded the eruption as C but this may be high and we suggest here, Hartmann B; VEI 2.

1902–1904: Strong fumarole activity preceded lava effusion in the north and northwest parts of the crater (Hartmann, 1934b). A lava dome began to grow east of Mesdjidanbaru, the precursor to the East Dome (G. Anjar, Fig. 8). In February, a minor explosion tossed altered lithic blocks and breadcrust bombs (?) beyond the crater (Anonymous, 1904a,b, 1905). In 1903, "Merapi was more or less active the whole year without being able to speak of a definite eruption" (Anonymous, 1905). Incandescent rockfalls occurred from the north side of the growing dome in January, shifting then to the southeast. The dome height above a fixed local reference was 70 m in January and 80 m in April, compared to 34 m in 1888. No explosions occurred and ash falls reported locally were produced from convecting ash clouds associated with dome avalanches (Anonymous, 1904b, 1905). However, Hartmann (1934b) mentioned explosions and rated activity as Class B. A regional earthquake in June, felt from Surakarta to Yogyakarta, was followed days later by "more violent eruptive activity" (Anonymous, 1905; Hartmann, 1934b). Increased growth of the eastern dome led to lava tongue collapses toward the Woro, Opak and Bagor rivers (Fig. 2; Anonymous, 1904b; Kemmerling, 1921). The "quiet outflow of a rather sticky lava" on steep dome slopes was regarded by Hartmann (1934b) as a fore-phase to activity in January 1904. "Of importance is the shifting of activity to the southeast side" (Kemmerling, 1921). Hartmann considered as remarkable that the volcanic activity had shifted suddenly into the eastern summit without apparent fore-signs, as lava discharge to the west seemed easier. Subsidence of a shallow magma chamber was interpreted to have caused a depression east of the dome.

Earthquakes shook the mountain on 18 January and on 22–23 January 1904, a violent explosion produced a "glowing rock rain" with "glowing streaks on the

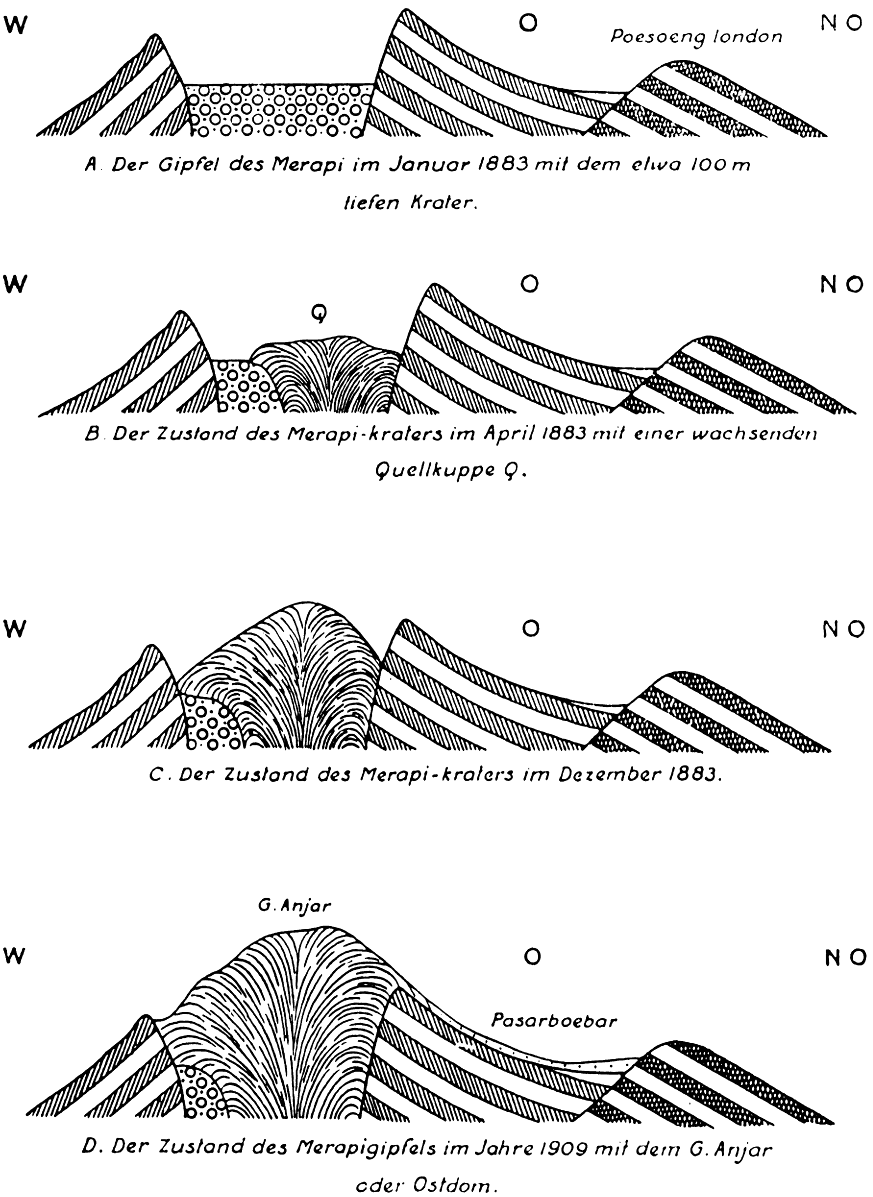


Fig. 11. Original cross sections of Merapi showing successive views of the growing lava dome on the Merapi summit between January 1883 and 1909 (Neumann van Padang, 1931). View west to east, then to northeast through the old crater wall at Poesoenglondon (cf. Fig. 8, 17). A. Summit in January 1883 with crater depth about 100 m; B. Condition of the crater in April 1883 with a growing dome; C. Condition in December 1983; D. Condition in 1909 with G. Anjar (or East Dome).

slopes" and roaring noise; the paroxysmal phase occurred on 30 January (Hartmann, 1934b; Anonymous, 1904b). Several explosions "partially created" the Woro breach (Fig. 13; Hartmann, 1934b) and caused nuées ardentes that travelled 6 km, "radiating a light red glow" to the east–north-east and producing a heavy ash fallout in Bojalali (Fig. 2). Weak activity then followed and heavy rains mobilized lethal lahars and caused phreatic explosions. The eruption ended with minor activity in June, when

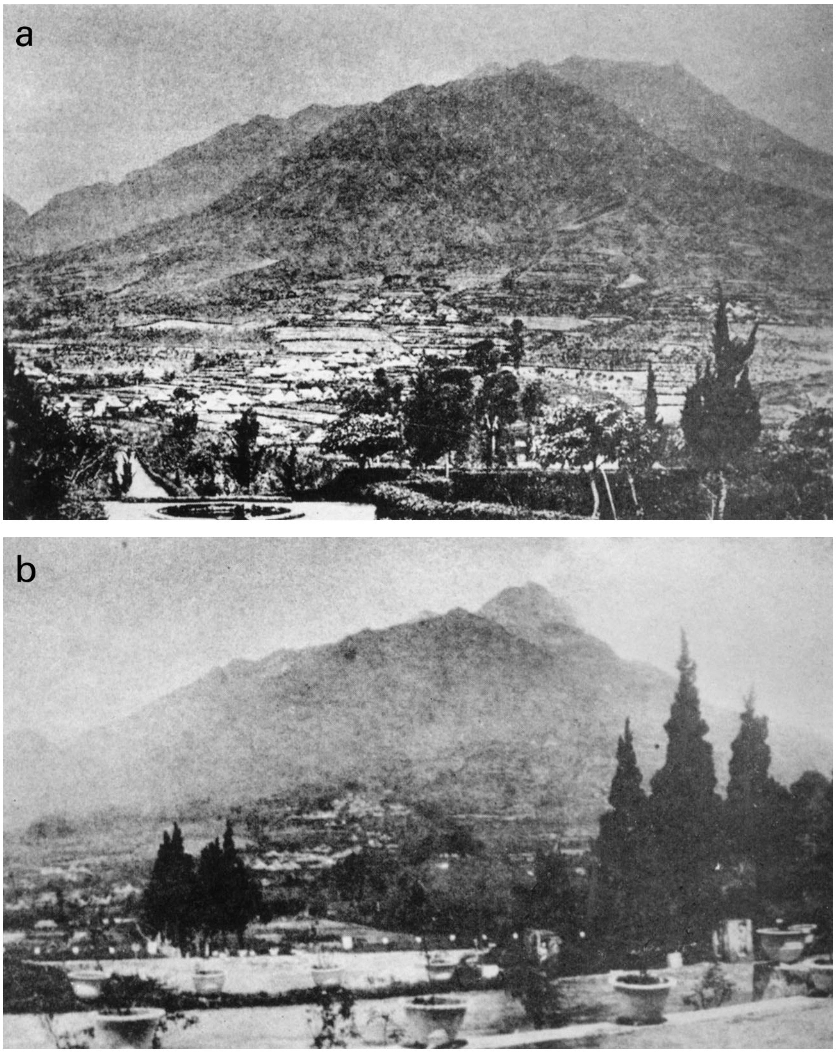


Fig. 12. Merapi as seen from Selo village on the north foot of the mountain (Fig. 2) (Minakami et al. 1969). a. April 1886. The flat summit morphology is controlled by the 1872 crater rim (cf. Figs. 9 and 11). b. 1 August 1920. West Dome protrudes above the summit. c. 30 August 1968. The summit is comprised of a stack of lavas from 1953–1955, then the 1956 lava flow descending to the right, with the summit point at top right in 1948 lava (cf. Fig. 33). Selokopo-duwur is the sharp top of the dark ridge in front of the summit in all three photographs (the identification in Minikami et al. is in error). Compare Fig. 30 for an identification of landmarks in 1953.

flowing lava and glowing avalanches were reported (Anonymous, 1904b; Hartmann, 1934b). Sixteen deaths from burns and 20 injuries were caused by the activity in January, "plantations were scorched, and houses set afire" (Kemmerling, 1921). Hartmann B; VEI 2.

1905–1906: In January 1905, an eruption less-violent but otherwise similar to that in 1904 occurred, starting with tephra fallout and nuées ardentes. A lava flow followed near the Woro breach (Fig. 13). In June, another explosive (?) phase occurred with a nuée ardente that advanced 4 km down the Woro valley (Hartmann, 1934b). The dome geometry is shown in Fig. 8. Small explosions occurred near the Woro breach at the end of January 1906, and the explosions increased in severity until 28 February, when a violent eruption ensued. Nuées ardentes swept through the re-opened Woro breach, after which lava was extruded

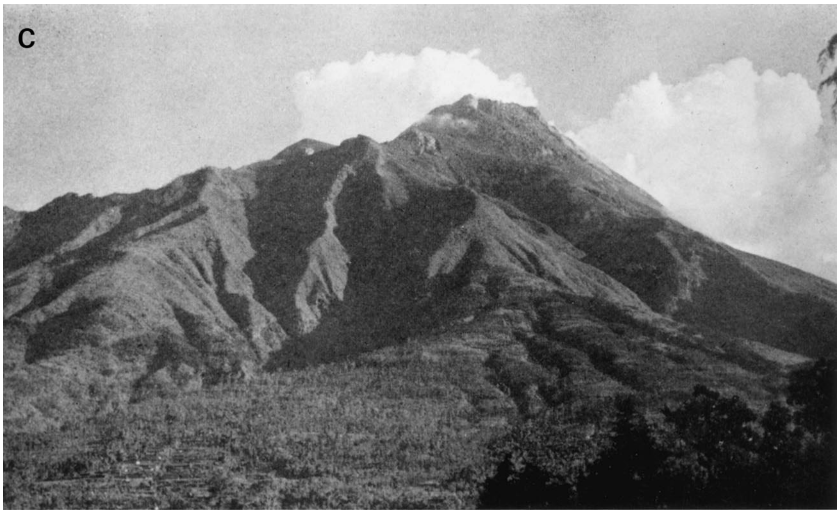


Fig. 12. (*continued*)

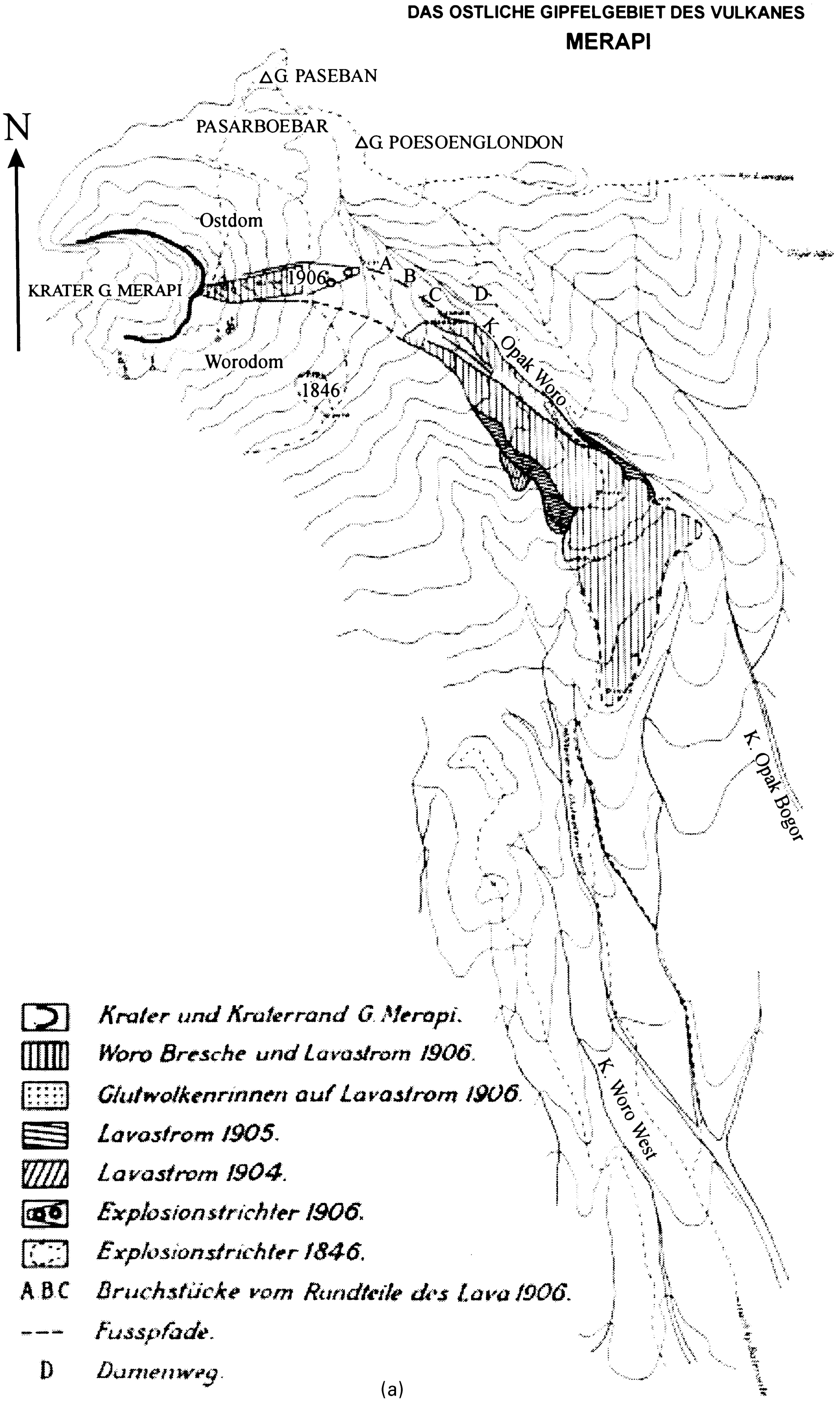
on the high flank and covered the lava of 1904 and 1905 (Fig. 13). This flow descended to the 2230-m level (Hartmann, 1934b). The dome resumed growth and enlarged beyond the Mesdjidanlama crater (Fig. 6), causing gravitational collapses (Anonymous, 1908). A new explosive phase started in May 1906. Hartmann B; VEI 2.

1907–1908: Minor explosive activity and ash rains were reported by local inhabitants (Anonymous, 1909). Hartmann (1934b) concluded that the events of 1904–1907 in the Woro area were similar to those of 1930–1931, with forephases with lava extrusion, main and gas phases with breach formation and nuées, and after-phases with more extensive lava advances. He considered 1907–1908 as years of quiescence, although some dome growth was reported for 1908 (Wurth, 1914). Hartmann A; VEI 1.

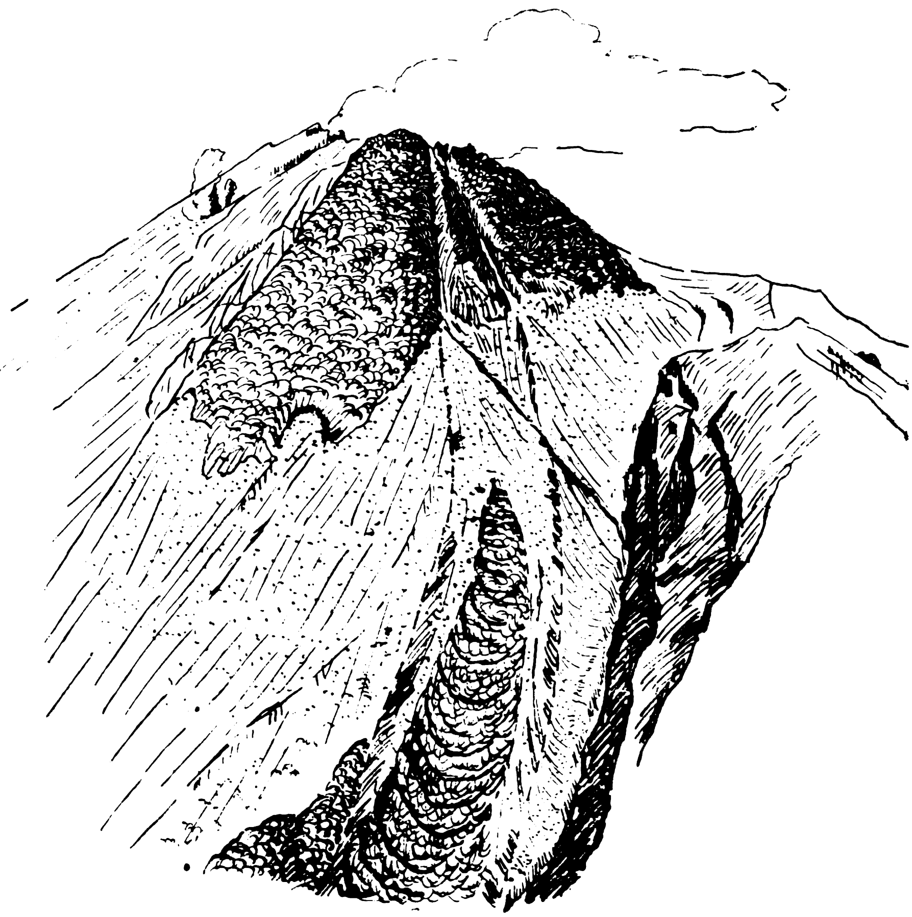
1909–1913: In 1909, the locus of active volcanism shifted towards the northwest, and the advancing dome lava overrode the crater rim; "only the western part of the rim is free of lava cover" (Figs. 8 and 11; Kemmerling, 1921). A few nuées ardentes were reported during 1909 and 1910, probably due to minor dome collapses (Wurth, 1914). The dome G. Anjar continued growth through 1911, especially at the northwest side, with the summit taking on a more symmetric shape (Kemmerling, 1921). On the west side of G. Anjar, a second summit dome rose in 1911–1912 (Fig. 8), and ultimately it became higher than G. Anjar by July 1912. This "west dome" had an unstable front on the southwest that collapsed periodically, generating nuées ardentes toward the Batang (Fig. 14; cf. Wurth, 1914; Taverne, 1933). By 1913, the west dome had grown to 2968 m, whereas G. Anjar was at 2910 m, a decrease in height of 8 m since 1909. The volume of G. Anjar was 25 million m^3 above the old rim (Kemmerling, 1921). Activity ended in May 1913. Hartmann A; VEI 1.

1915: From 28 March to 15 May, renewed eruptive activity started with a minor destructive phase and ended with dome growth (Kemmerling, 1921). Rock avalanches occurred. Hartmann A; VEI 1.

1920–1923: On 25 July, an eruptive episode began with explosions that excavated a cavity west of the summit, below the dome of 1911–1913. In late July, "suddenly more steam began to vent at intervals from the lava plug, although Merapi had already been 'smoking' for several months more strongly than normal, without it leading to a lava discharge" (Kemmerling, 1921). Summit topography is shown in Figs. 15 and 8. A dome rose in this crater and the activity ended in February 1921 (Anonymous, 1921). On 12 October 1920, inhabitants near the Blongkeng and Senowo were "surprised by hot ash clouds," and 35 were killed (Kemmerling, 1921). The scorching was limited to areas adjacent to ravines, and Kemmerling concluded that the activity was not associated with an explosive outburst. The border of the


DAS OSTLICHE GIPFELGEBIET DES VULKANES
MERAPI
N
ΔG. PASEBAN
PASARBOEBAR
ΔG. POESOENGLONDON
Ostdom
1906
A
B
C
D
KRATER G. MERAPI
Worodom
1846
K. Opak Woro
D
K. Opak Bogor
K. Woro West
Krater und Kraterrand G. Merapi.
Woro Bresche und Lavastrom 1906.
Glutwolkenrinnen auf Lavastrom 1906.
Lavastrom 1905.
Lavastrom 1904.
Explosionstrichter 1906.
Explosionstrichter 1846.
A B C Bruchstücke vom Rundteile des Lava 1906.
Fusspfade.
D Damenweg.

(a)



(b)

Fig. 13. The eastern summit region of Merapi, and the upper Woro valley (Hartmann, 1934b) (a) Map. Legend: crater rim (1909?), heavy solid line; Woro breach and 1906 lava flow, vertical lined pattern; nuée ardente channel from 1906 lavas, stippled; 1905 lava flow, right-slanting lined pattern; 1904 lava flow, left-slanting lined pattern; explosion sites in 1906, small circles; explosion site in 1846, dashed loop; A–C, fragments at the margin of the 1906 lava path; footpaths, dashed lines; upper tributaries of the Opak (center right) and Woro (lower right) drainages, solid lines. The summit dome is *Ost dom* (East Dome, or G. Anjar); Hartmann refers to the part of this dome south of the Woro breach as Woro Dome. (b) View from east of the eastern and southeastern part of the summit dome, showing a narrow lava flow from the period 1904–1907 (mainly 1906).

devastated area coincided with the tip of the hot block-and-ash ladu, located about 1 km upstream of the Maron observation post (Maron is near the 960.8-m benchmark upslope from Gentong, Fig. 16).

On the morning of 12 October, people from Sisir, Deles and nearby villages (Fig. 16) had gone to higher fields to look after cattle and cut grass. The summit was not visible and many had gathered in clusters to protect themselves from rain showers, when a "remarkable noise in the Blongkeng and Senowo frightened them…they saw a 'sand' flow in the ravine…then it became dark and a hot wind blew across the fields, causing everything there to be steamed… Most were immediately killed or succumbed a few days later" (Kemmerling, 1921). A thin dusting of ash was soon "washed quite quickly" by rain, so that no stratigraphic record of the lethal cloud was preserved. Later, temperatures as high as

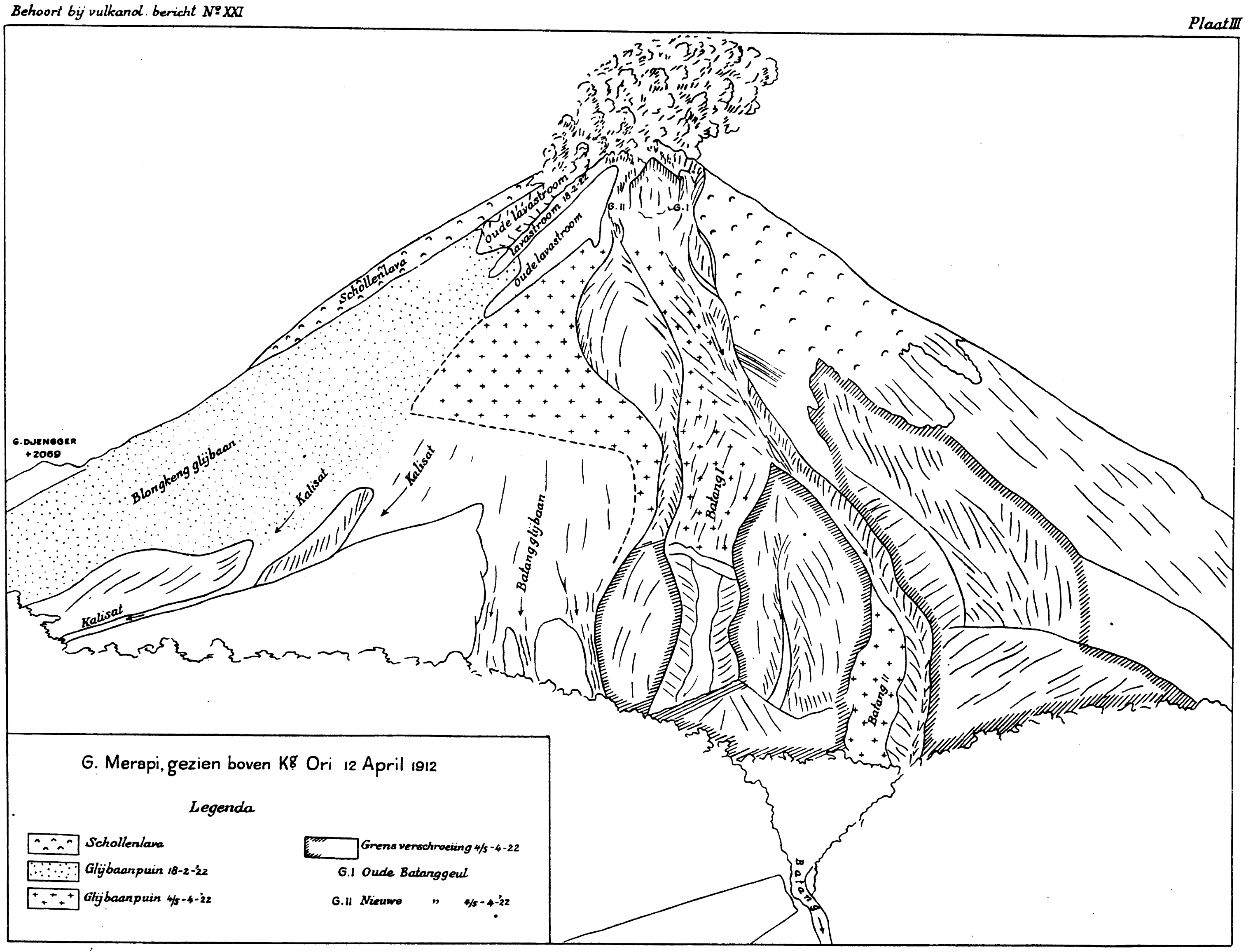


Fig. 14. Original sketch of Merapi from G. Ori on the Batang sector (southwest), 12 April 1912 (Taverne, 1933). See Fig. 16 for location of G. Ori. Legend: Block-lava (*schollenlava*), arc pattern; avalanche glide slope debris (*glybaanpuin*) to the Blongkeng, February 1922, stippled; glide slope to the Batang, April 1922, crosses; boundary of scorched area in April 1922 (*grens verschroeiing*), hachured; old (G.I) and new (G.II) channel passages from the dome to the Batang. Also shown are old lava flows (*oude lavastroom*). Place names from left to right include G. Djengger (lower skyline), and Kalisat and Batang drainages.

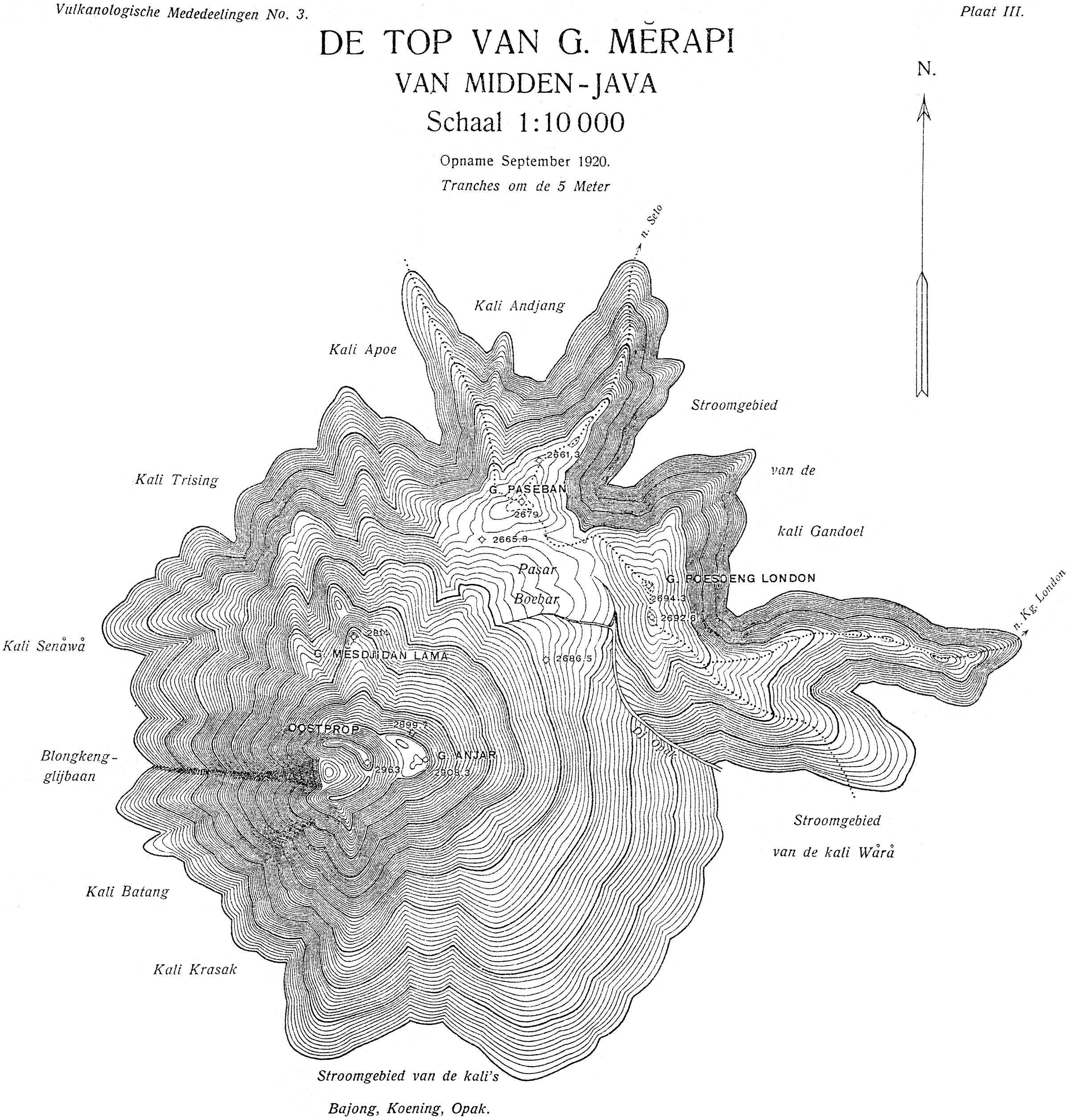


Fig. 15. Topography of upper part of Merapi in September 1920 (Kemmerling, 1921). Contours 5 m. River drainages (Kali) surrounding the mountain are named. Topographic peaks noted as G. Mesdjidanlama, G. Paseban, G. Poesoenglondon (cf. Fig. 9). West Dome (*mis-labelled,* as *Oost prop*) and G. Anjar are the summit lava domes (see Fig. 8).

170°C were measured in the ladu deposits, representing minimum emplacement temperatures.

Heavy rains in early October could have helped to trigger the dome-collapse nuées (Kemmerling, 1921). Fig. 12b shows the summit dome complex from Selo in August 1920, before the events of October occurred.

Kemmerling made the first scientific observations

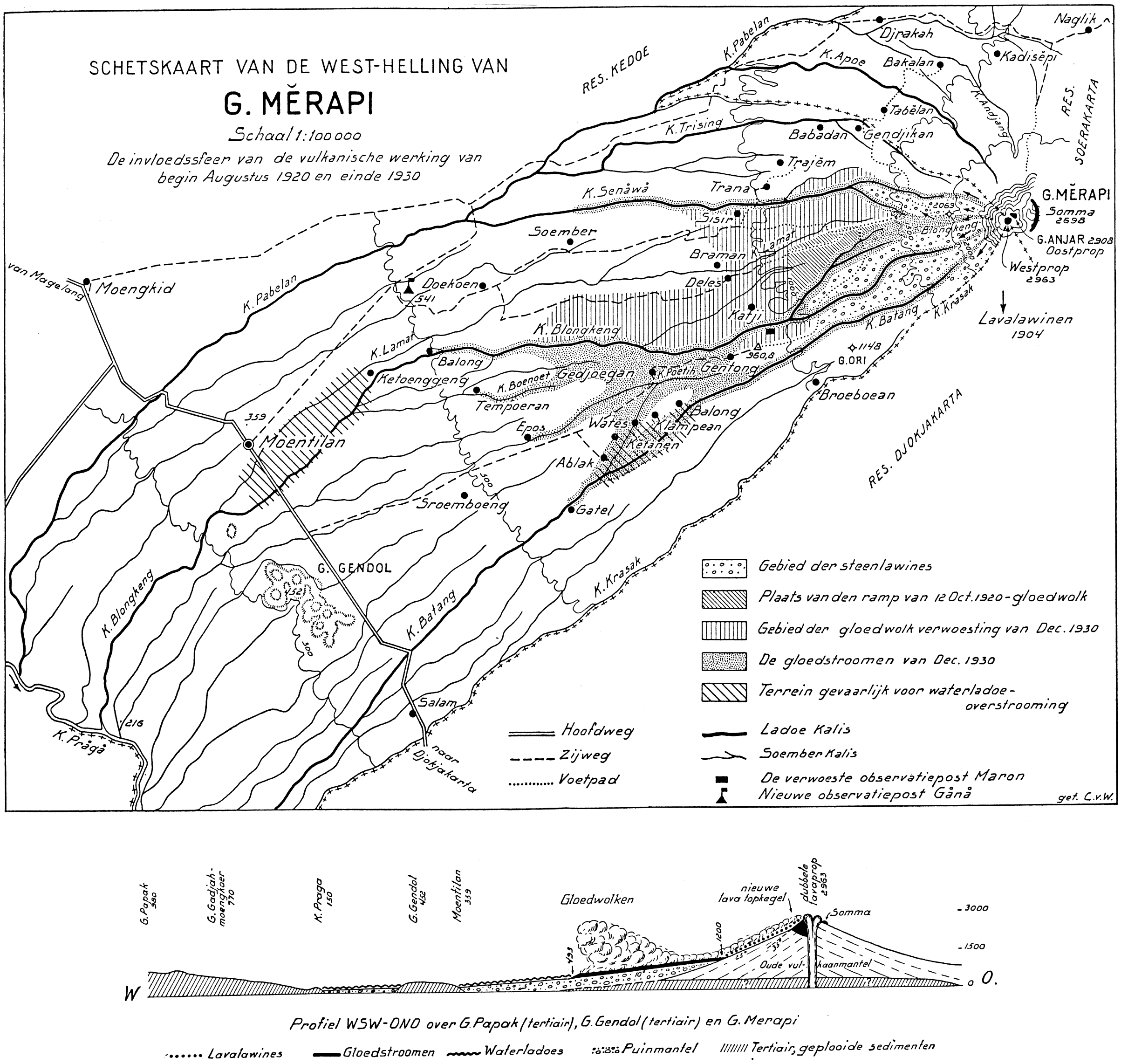


Fig. 16. Original sketch map of the western flank of Merapi indicating nuées ardentes deposits of 1920 and 1930 (Kemmerling, 1931). Legend: lava-block avalanches (*steenlawines*), pebble-pattern; nuées ardentes deposits of 12 October 1920 (*gloedwolk*), fine slant pattern; nuées ardentes deposits of December 1930, vertical-lined pattern; "glowing currents" of December 1930 (*gloedstroomen*), stippled; lahar overspill areas (*waterladoe-overstrooming*), broad slant pattern. Main roads, lesser roads, and footpaths shown by double-lines, dashed, and dotted lines, respectively. Streams with block-and-ash flows (*ladoes*) are shown by heavier lines. Named villages, dots. Section below from west to east, from G. Papak (off map) through G. Gendol (interpreted as Tertiary) through Merapi. Legend: lava-block avalanches (*lavalawines*), dots; "glowing currents" (*gloedstroomen*), heavy line; lahars (*waterladoes*), wriggle line; debris fan (*puinmantel*), gravel pattern; Tertiary sediments, lined pattern. Active nuée ardente (*gloedwolken*); double-dome (*dubbele lavaprop*) refers to West Dome (*West prop*) and East Dome (*Ost prop*) on summit; newest lava extrusion area shown in black, on west summit area over older edifice material (*oude vulkaanmantel*).

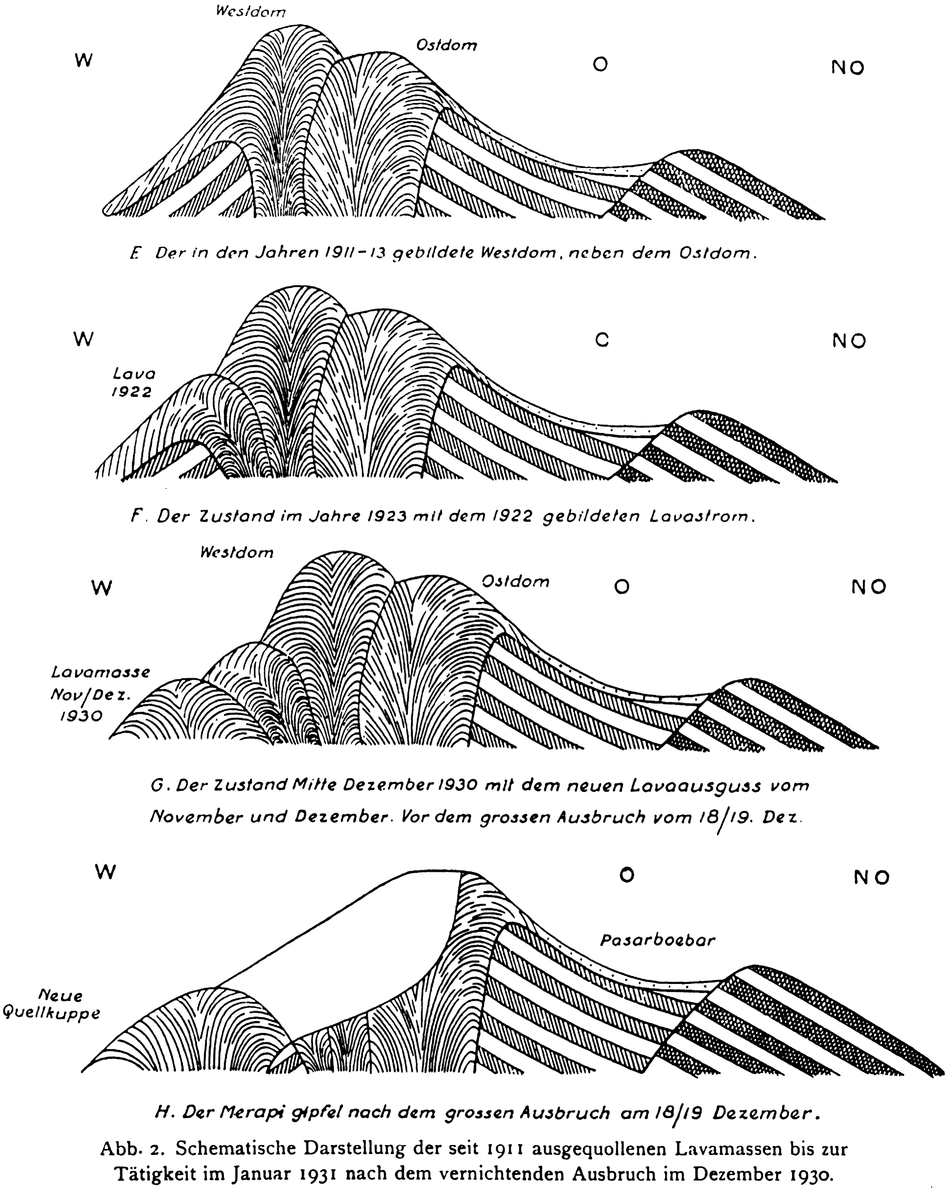


Fig. 17. Original cross sections showing successive views of the lava dome complex on the Merapi summit between 1911 and December 1930 (Neumann van Padang, 1931). View west to east, then to the northeast through the old crater wall at Poesoeng London (continuation of Fig. 11). E. Summit in 1911–1913 showing rise of West Dome through East Dome (*Ost dom,* a.k.a. G. Anjar). F. Condition in 1923 showing lava flow of 1922, vented between West Dome and the old crater wall on the west; G. Condition just before the eruption of 18–19 December 1930, showing November–December 1930 lava vented under the conduit lava of 1922; H. Summit in January 1931, after the large eruption of 18–19 December 1930; section shows the region of the dome complex destroyed by collapse. New lava forms a small dome inside the cavity.

Fig. 18. Merapi as viewed from the west in December 1930, showing the summit crater from the December 1930 eruption, and the devastation brought by the ladu (block-and-ash flow) and scorching cloud deposits in the midst of the richly-cultivated plain with terraced rice-fields and tree-screened villages. Sketch from a photograph in Neumann van Padang (1933).

of pyroclastic currents at Merapi, which he compared to the *nuées ardentes* described by Lacroix at Mont Pelée. He noted that the "disaster should not be imputed to an *eruption* of Merapi, but to a secondary phenomenon, namely sliding and lava-block avalanches." Kemmerling's observations led to the classification proposed by Escher (1931, 1933a), in which Merapi-type nuées were first named.

On 18 February 1922, a series of explosions accompanied the passage of lava and block avalanches from the west dome from a place where, before the eruption, "fire glow" was visible at night (Anonymous, 1923; Neumann van Padang, 1934). "Unexpected" (i.e., with no precursors observed) rock avalanche activity directed toward the Blongkeng occurred 4–5 April and glowing lava was reported on parts of the dome. Further activity occurred in August 1922, after which time the volcano reached a "state of comparative rest" (Anonymous, 1923). Vapor emissions and minor rockfalls were reported after 1923 (Anonymous, 1924), and a plateau-like depression was described on top of G. Anjar, "probably as a result of the sinking-back of lava inside the dome." Fig. 17 shows a profile of Merapi in 1923, including the positions of various lava domes. Hartmann B; VEI 2.

1924: Gas emissions stronger than in 1922, increased temperatures, breach widening and rock avalanches were reported (Anonymous, 1924; Taverne, 1925). An Omori tremometer (seismograph) was purchased in Japan and installed at Maron in February. Heightened activity on 10–11 September included summit "fire phenomena" and suggested a new eruptive episode. A seismic swarm preceded the first rock avalanches by 36 hours. These seismic events were recorded but not felt at Maron, although some were felt on the east flank. The seismic unrest was observed only before and at the start of eruption. Since 1924, systematic temperature measurements at summit fumaroles have been recorded (Neumann van Padang, 1963). Hartmann A; VEI 1.

1925–1929: A period of dormancy was reported for this period of time at Merapi (Purbo and Suryo, 1980), the "longest in this century" along with 1935–1939, 1962–1966, and 1987–1992.

1930–1931: Numerous tremors were recorded in January 1930 and their occurrences increased to 25 November, just after the first appearance of lava (BNEIVS, no. 39–40).

The seismic data and increased temperature of fumaroles were used to anticipate the eruption (BNEIVS, no. 39–40). Lava broke out under the pre-existing domes, 250 m under the summit, and

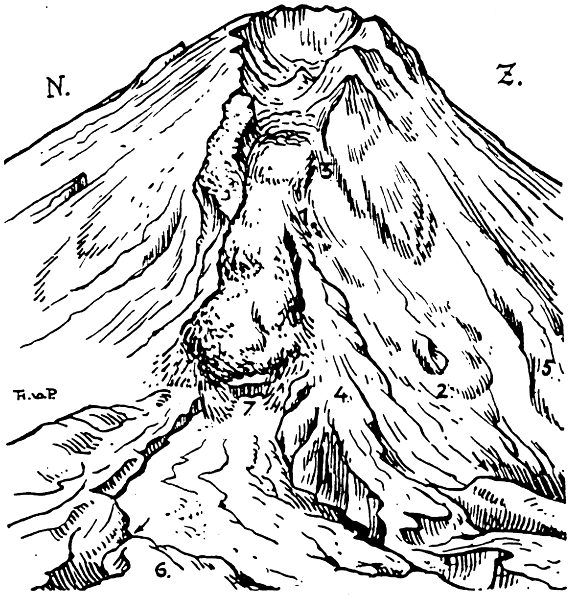


Fig. 3.

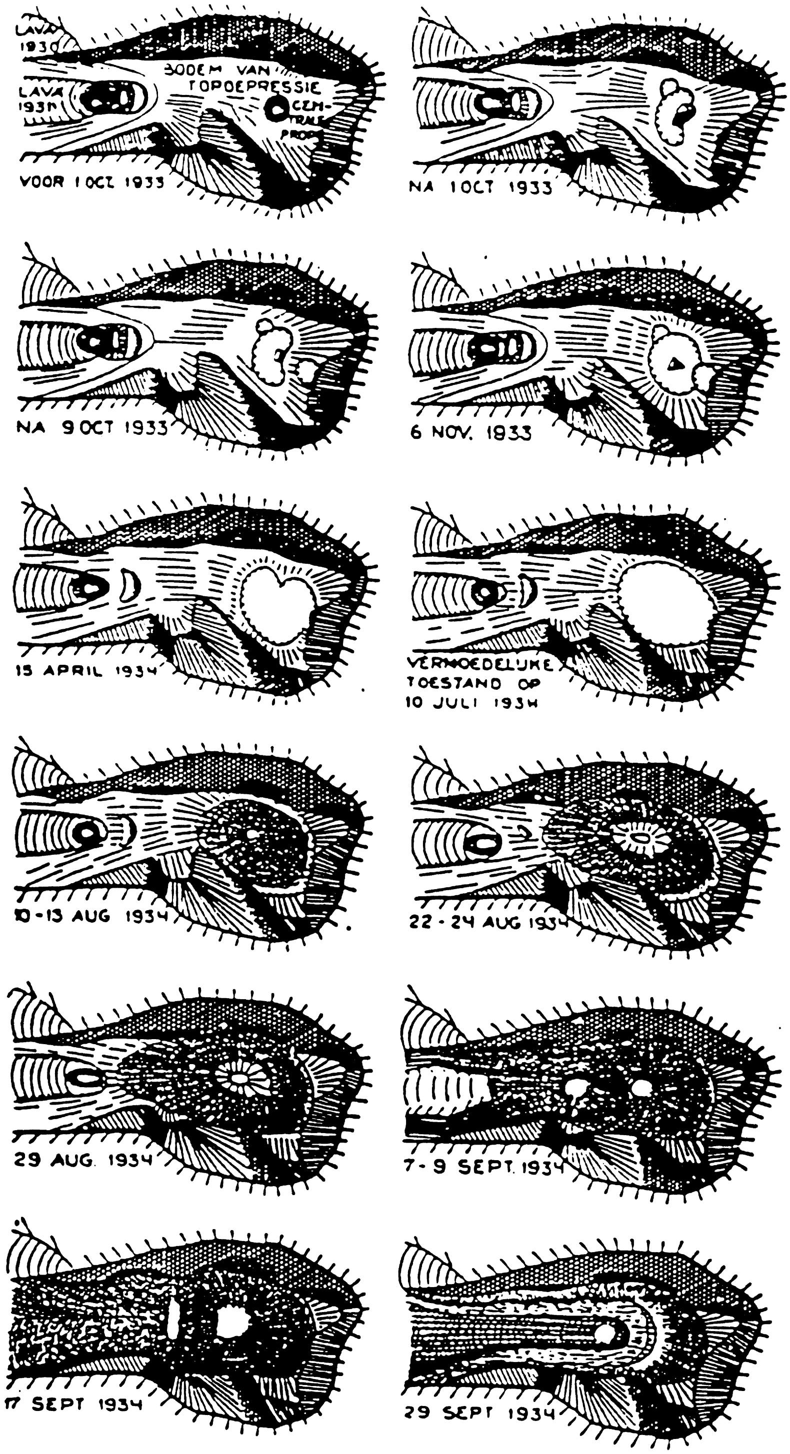
DE MERAPI op 28 Mei 1931 naar een 'schets van af de G. Gono.
1. Oorsprong der gloedwolken
2. Eindpunt daarvan op 24 Mei
3. Oorsp. der gl. w'n. begin '31
4. Rug t. K. Blonkeng en K. Saät
5. Rug van de Patoek alap'
6. Rug t. K. Bl. en K. Lamat
7. Einde lavatong van vroegere uitbarsting.

Fig. 19. Original sketch of Merapi from the west on 28 May 1931, by Th. W. van der Plas (Grandjean, 1931c), showing the open crater of the December 1930 eruption and the lava tongue emerging from a vent near the foot of the crater. Legend: 1. source for nuées ardentes; 2. end position on 24 May; 3. source of nuées, beginning 1931; 4. Blongkeng (left) and Saat (right) drainages; 5. Patoek drainage; 6. Blongkeng (right) and Lamat (left) drainages.

effusion remained steady until 18 December (Fig. 17). Lava blocks fell from the flow front down the Senowo, Batang and (mainly) the Blongkeng valleys. The classic description is by Neumann van Padang (1933, 1931).

The culminating phase with spectacular nuées ardentes occurred December 18, 23 days after the appearance of lava. The first big nuée ran 6 km, and a few hours later another reached 11 km (Fig. 16; cf. Kemmerling, 1931). More occurred the next day, with a catastrophic nuée at 7:30 p.m. that travelled 12 km. These nuées caused havoc; 20 km^2 with 13 villages were annihilated, 23 were partly destroyed, and 1369 people and 2100 animals were killed. Included in this number was the NEIVS observer Bardi Kartodihardjo, who had stayed at his post. A block-and-ash (ladu) deposit 10–15 m thick and with temperature over 400°C filled the valleys (Hartmann, 1933), and thick ash-cloud surge and fall deposits mantled the flank with 1–40 cm of lapilli and ash (Fig. 18). Mud rain was reported in Yogyakarta.

A vast summit depression, 850-m long and open to the west to an elevation of 2150 m, resulted from the paroxysmal activity and indicated the gravity collapse of the old dome complex as well as the new lava. The collapse was preceded by heavy rains on 8–9 December and 9 hours of rain on 16 December. These events are often depicted in texts as classic Merapi-type nuées ardentes, but the involvement of voluminous solidified old domes in the process, the undermining of these domes by fresh lava, and the possible destabilizing influence of water or steam pressures associated with heavy rain infiltration through the old domes, suggests that the overall process was much more complicated than for typical Merapi-type nuées ardentes. Instead, the catastrophic activity


LAVA 1930
BODEM VAN TOPDEPRESSIE
LAVA 1931
CENTRALE PROP
VOOR 1 OCT. 1933
NA 1 OCT 1933
NA 9 OCT 1933
6 NOV. 1933
15 APRIL 1934
VERMOEDELIJKE TOESTAND OP 10 JULI 1934
10-13 AUG 1934
22-24 AUG 1934
29 AUG. 1934
7-9 SEPT. 1934
17 SEPT 1934
29 SEPT 1934

seems to have represented a hybrid between a volcanic debris avalanche and a nuée ardente. In addition, there is the question of the influence of explosions (vertical or directed) during various stages of the process. The proposition of some directed explosions was raised by Grandjean (1931a–c) but rejected by Kemmerling and Neumann van Padang. We think the proposition may have merit, because rapid unloading is likely to promote explosive activity in pressurized lava and/or magma, and we believe it likely that some of these explosions could have been inclined, given the geometry of the dome complex (Fig. 17). Some evidence regarding these questions might be gained by detailed modern study of the deposits, which to date has not been attempted.

The effusive phase began January 1931 when lava rose in the higher part of the depression and developed into a flow (Fig. 19). The lava effused at variable rate and frontal collapses generated small nuées ardentes (BVSI, nos. 41–50; Grandjean, 1931c) which intensified during June and July. Grandjean (1931c) claimed that some were of Peléean-type, with lateral explosions. Activity stopped in September, but heavy rains mobilized hazardous secondary lahars with still-hot debris. Hartmann B; VEI 3. The volume of eruption products was estimated as 26 million m^3 by Siswowidjoyo et al. (1995), equivalent to a cube about 300 m on each side. An electric rain gauge was installed in December 1931 to warm of lahar-triggering storms, and a comprehensive treatment of lahars in 1930–1932 was written by Schmidt. In 1932 a small dome was reported (Neumann van Padang, 1963), as well as small rockfalls and gas emissions (BNEVS, nos. 51–60). Solfatara temperatures to 900 deg C were measured (Neumann van Padang, 1963).

1933–1934: An explosive phase began 1 October, created a small crater and generated fountain-collapse nuées ardentes; the activity lasted until April 1935 (BNEIVS, nos. 61–66; Neumann van Padang, 1963). "An increase in gas and pressure probably indicated a period of stronger activity" (Hartmann, 1935b). A small eruption occurred on 25 November, and a red glow was observed at the summit. On 30 November a funnel-shaped eruption column shot 500 m above the summit and bombs fell on the upper flank between Trising and Senowo valleys (BNEIVS, nos. 61–66). Similarly on 12 December, bombs fell around the flanks and the summit resembled "a single mass of fire." Explosions were heard that lasted 3–4 min and were followed by the sounds of avalanches for 5 to 6 min (BNEIVS, nos. 61–66). These events changed the summit morphology (Fig. 20).

From February 1934, signs appeared of a slowly building second explosive phase, lasting until 13 May with increasing occurrences of nuées ardentes (Hartmann, 1935b). Sporadic eruptions occurred on 17 February and in March; these were notable for their audible explosive character and observed gas activity, but produced only minor ashfall (BNEIVS, nos. 67–70). On 6 April, a few small nuées occurred, but on the 21st a stronger eruption occurred that lasted 8 min and produced fountain-collapse nuées ardentes (Fig. 21). On 27 April, a 700-m vertical eruption column caused widely dispersed airfall. This may be the event referred to in Anonymous (1934), viz. "…a violent eruption in Merapi's crater occurred following a violent tectonic seaquake off the south coast of Java." As a result of these eruptions, the 1930 dome was destroyed by May and a crater had formed in its place (Hartmann, 1935b). In June, a brief explosive phase began with eruption columns to 1000 m, bomb falls, and ignition of grass fires. On 10 July, an eruption column rose 700 m (BNEIVS, nos. 67–70), possibly destroying a small dome emplaced after 23 June. Hartmann recognized two eruption subclasses: the first, relatively infrequent, involved block-and-ash eruptions producing clouds of "majestic appearance"; the second, predominant in number, were gas eruptions that "emphasize the purely explosive character of this phase."

Between July and September, a lava dome grew in

Fig. 20. Original sketch maps of changes within the summit crater of Merapi between October 1933 and August 1934 (BNEIVS, No. 69). The crater originated with the eruption of December 1930, and the vent for the 1930 lava is shown in the upper left figure that represents conditions before 1 October 1933. The time sequence is from left to right, and top to bottom. Destruction of a small lava dome on the crater floor was followed by progressive enlargement of an explosion crater. A new dome formed after 10 August 1934, that grew into a complex lava tongue that flowed around, and then over, the lava of 1930. Simultaneously, in September, the hotter western part of the dome began to separate from the cooler eastern part, and ultimately formed a horse-shoe shaped cavity inside of which further flows developed.

the new crater, with pieces of the old floor floating near the rim, and corrosive gases whistling under pressure from fissures and occasionally tossing red-hot clasts to the rim (Fig. 20). After August, incandescent rockfalls could exit from the crater on the west (Fig. 19; BNEIVS, nos. 67–70). The abundance of gas released from bursting lava blocks suggested increased magmatic gas content. On 19 September, the western part of the new dome flowed away from the cooler stationary eastern part, leaving a horseshoe-shaped gap. Lava flux decreased in October, then accelerated again, leading to collapses on 17 November that resulted in destructive nuées running 7 km down the Senowo. No vegetation remained standing in the valley and trees 70 cm diameter were toppled. The collapse scar was soon repaired by fresh lava. Hartmann C; VEI 2.

In 1935, the lava dome continued to grow and to shift further to the west, and later in the year a few small nuées ardentes were shed by the growing dome. The volcano remained seismically active.

Hartmann (1935b) suggested that Merapi had shown new eruptive mechanisms during the 1933–1934 events. A moderately gas-charged magma emerged with near-surface energetic gas escape and produced fountain-collapse nuées. Following strong degassing, an "after-phase" lava dome then would grow, and an increase in lava flux and resulting instability would lead to a large dome-collapse nuée. Hartmann also attributed these eruptions and those of 1837–1838, and 1846–1847 to class C. The dearth of explosions during the effusive phase of 1934 had "startling similarity" to 1930–1931. He also suggested that "probably many of the described effusive 1931 pre- and post-phase 'explosive' events were not really explosive, but had been viewed at too great a distance for certain judgment." Merapi's 1934 activity rebuilt much of the summit region destroyed in 1930–1932. Finally, Hartmann noted that the possibility of a rim breakthrough to a different sector had "logically increased."

1935–1939: Gas emissions and small rockfalls were reported, and a warning siren was installed at one observation post (BNEIVS, nos. 75–86). From April 1935 to December 1939, Merapi was inactive (Neumann van Padang, 1963).

1939–1941: On 13 December 1939, an explosion occurred in the higher part of the crater formed in 1930 (Van Bemmelen, 1949; BNEIVS, no. 95–98), and small nuées descended the western, southern, and southeast slopes. An explosion pit with a diameter of about 100 m and depth of 50 m was formed in the 1934 lava. A second explosion was seen 23 December, and on 24 January 1940 an eruption plume reached a height of 3–3.5 km, generating hot avalanches in Gendol and Woro valleys (Neumann van Padang, 1963). The three explosions were described by Van Bemmelen as the *ultra-vulcanian* type, following the usage of Perret (1937), who used the term to describe the earliest explosive events of the Mont Pelée eruption of 1929–1932, with the ejecta consisting of still-hot material from the older dome, rather than new magma. In February, a lava dome then grew quietly until the lava reached the west rim of the depression in August (Fig. 23), whereupon rockfalls and small nuées ardentes rolled down the western slope. Dome height was 76 m in

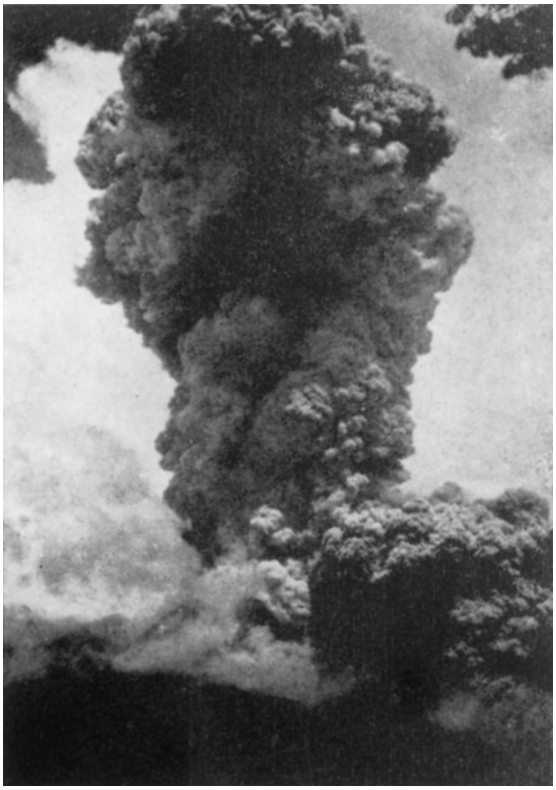


Fig. 21. Fountain-collapse nuée ardente in a vulcanian explosion at Merapi on 21 April 1934 (Van Bemmelen, 1949). The author referred to this as an "*explosion type*" nuée ardente.

mid-September and growth ceased soon after. The tiltmeter at Babadan had remained steady over the year. Despite the initiating explosions, Van Bemmelen rated the eruption as Hartmann A. One wonders whether Hartmann might have considered a C or B ranking based on these explosions, or conversely, whether some of the abruptly initiated eruptions of the past, that had been ranked C, might have been of similar character. VEI 2.

In December 1940 and January 1941, the dome top subsided (Fig. 23); this was interpreted by Van Bemmelen as "shrinkage of the cooling mass" (cf. Fig. 16 in BNEIVS, nos. 95–98; Van Bemmelen, 1949, Fig. 58 Ie) (see also the description for 1920–1923). This depression marked the end of the 1939–1940 eruptive episode. Similar depressed domes have been observed at Lascar, Chile, precursory to vulcanian explosions (R.S.J. Sparks, written communication), and also at Popocatepetl, Mexico, where the relation of subsidence to explosions is unclear (C. Newhall, written communication). Lava flux has been estimated for 1939–1940 and for a similar episode of activity in 1942–1943 (Fig. 22; Van Bemmelen, 1949, p. 200). Photographs of the cone at this time are shown in Minakami et al. (1969).

In 1941 new countermeasures against eruptions and lahars were issued. Concentric danger zones were divided into radial sectors, and alarm systems devised for specified sectors (BNEIVS, no. 95–98). The "so-called *forbidden zone* was established," dangerous because of hazards from nuées ardentes and lahars, and a "second danger zone…menaced by very heavy eruptions…"

1942–1945: After 20 months of quiescence since September 1940, explosions with eruption clouds to 1 km and glowing bombs occurred on 30 May and in June 1942, preceded by a solfatara temperature rise (Van Bemmelen, 1949, Fig. 66; cf. Neumann van Padang, 1963). The initial activity, with "remarkable similarity" to that of 1939–1940 (BNEIVS, no. 95–98), occurred between the 1940 dome and the south rim (Fig. 23), lasted 13 min, caused an eruption plume 1 km high, and generated scorching block-and-ash flows between the Batang and the Woro (Fig. 24). On 8 June, a brief explosion originating beneath the lava dome shot obliquely to the NNW and blasted a notch in the north crater rim to form the Trising breach (Fig. 23). Remarkably, the activity, which lasted "almost unbrokenly for about three years" (Petroeschevsky, 1953), was monitored by Van Bemmelen while a "prisoner" of the Japanese occupation force. [Compare with the fate of Charles E. Stehn, Director of the Netherlands Indies Volcanological Survey since 1926; Stehn, who was a German, was interned as a prisoner by Dutch authorities at the start of World War II, and later transferred to Dehra

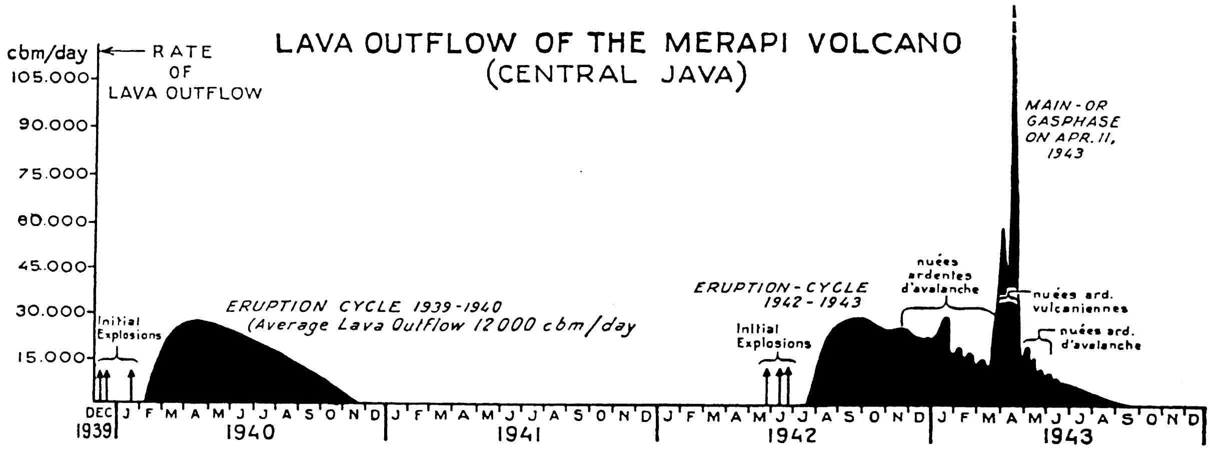


Fig. 22. Graphical illustration of eruption episodes at Merapi in 1939–1940 and 1942–1943 (Van Bemmelen, 1949). Rate of lava outflow in cubic meters per day is plotted against time. The first episode is designated Hartmann class A, and the second, class B. Despite the difference in rank, both are similar (apart from the "main- or gas-phase" on 11 April 1943, and both began with vent-clearing explosions. Note that in 1942–1943, dome-collapse nuées ardentes both preceded and followed fountain-collapse nuées of the main phase.

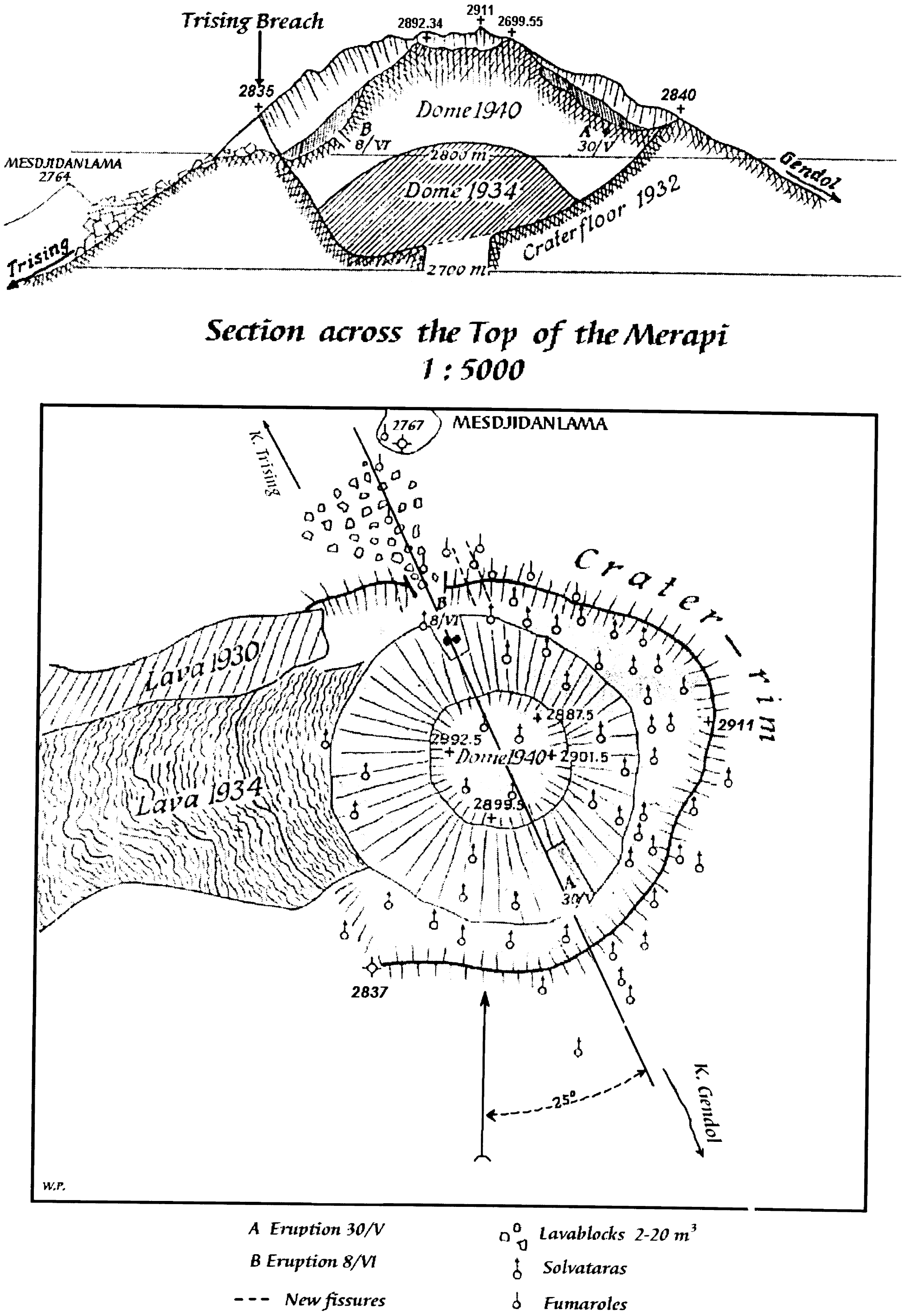


Fig. 23. Original section and map of Merapi summit in 1942, showing the lava dome of 1940, and buried dome of 1934. Explosion breaches formed in the 1940 dome on 30 May 1942 (toward Gendol valley) and on June 8, 1942 (toward Trising valley). Unpublished sketch, VSI files.

Dunn in British India, where he died (Neumann van Padang, 1983). Such are the fortunes of war]. New dome growth originated west of the 1940 dome (Fig. 25); its rate increased in July 1942, and rockfalls and nuées ardentes intensified (Fig. 26; Petroeschevsky, 1953). The nuées were short and their speeds were relatively slow, about 45–75 km/h. Fig. 27 shows a view from the northwest in July 1942. Seismic activity was noted, and in October after a series of rockfalls, tiltmeter data experienced a shift. Dome growth continued throughout the year and into 1943.

From 5 March to 11 April, 1943, dome growth was focused at a new vent through the southern half of the 1942 dome, and nuées rolled toward the Batang (Fig. 28). The activity between 20 March and 12 April was particularly energetic and represented the main phase. “The unwilling population of the Upper Batang sector was then forced by the field-police to evacuate on April 1, 1943” (Van Bemmelen, 1949, p. 223). On April 11–12 there were 52 nuées, some formed by severe explosions which created a crater about 80 m in diameter (Neumann van Padang, 1963). The nuées ardentes “indeed invaded the evacuated sector. After only three weeks of evacuation, the population could return to their dwelling places and restore the damage” (Van Bemmelen, 1949). (All this, remarkably, during the Japanese occupation). An electromagnetic seismograph to record “volcano sounds” was installed in 1943 (Van Bemmelen, 1949, p. 223). Following the events noted above, effusion of lava resumed as a tongue toward the Batang breach, with small collapse nuées; the volume of the lava flow reached two million m^3 by end of May. An excellent topographic map of the summit was made in July 1943 (Fig. 29). A “revival” of Merapi activity occurred after the tectonic earthquake of 23 July 1943, analogous to earthquake-triggered volcanic activity in South Sumatra in 1933 (Van Bemmelen, 1949). Activity concluded in October. Hartmann B; VEI 2.

Activity continued in 1944 with rockfalls, nuées ardentes and seismic events common (Petroeschevsky, 1953). In 1945, minor rock falls and occasional glow were observed from Merapi. Apart from the brief period in 1943, the period 1942–1945 was characterized mainly by effusion of gas-poor viscous lava. Damage produced during this period was limited. During 1946 and 1947, no significant activity occurred.

1948: On 29 September 1948, an explosion began a new effusive episode that caused “rains of glowing rocks” (Petroeschevsky, 1953). The new lava completely covered the 1942 and 1943 lava; rockfalls occurred about 25 times daily in November and December. We consider the initial explosions as comparable to 1939; hence, we suggest Hartmann A; VEI 2.

1949–1952: Merapi was inactive during this period (Purbo and Suryo, 1980).

1953–1956: On 2 March 1953, a thick cloud was observed near the summit and ashfall occured on the volcano flank (BVSI, no.100). The ensuing activity included dome growth spreading lava a few hundred meters toward the north (Fig. 33a), collapse-type nuées, and rockfalls (Fig. 30).

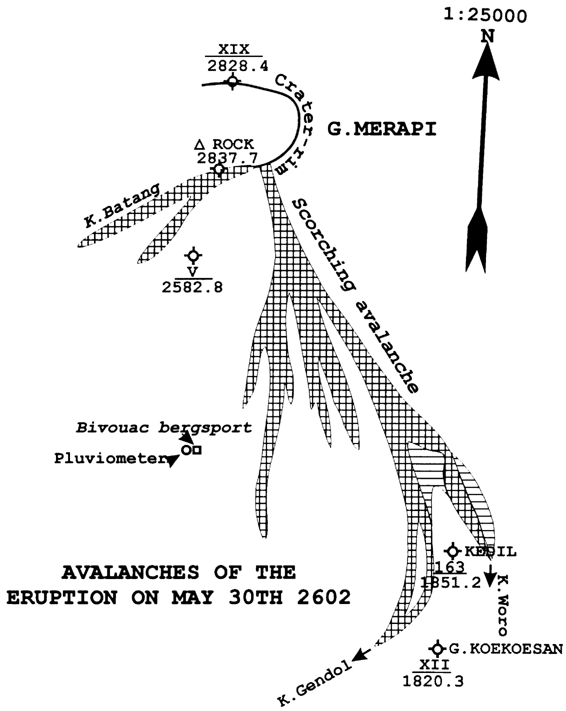


Fig. 24. Sketch map of the nuées ardentes (scorching avalanches) on 30 May 1942 in the Gendol and Woro valleys, with lesser nuées directed toward the Batang in the southwest. Redrawn unpublished sketch, VSI files. Scorched wood areas (singe zones) indicated by lined pattern. Javanese year 2602 indicates 1942. Note “Triangle rock” as triangle-symbol on rim; this reference point is used in a number of sketches.

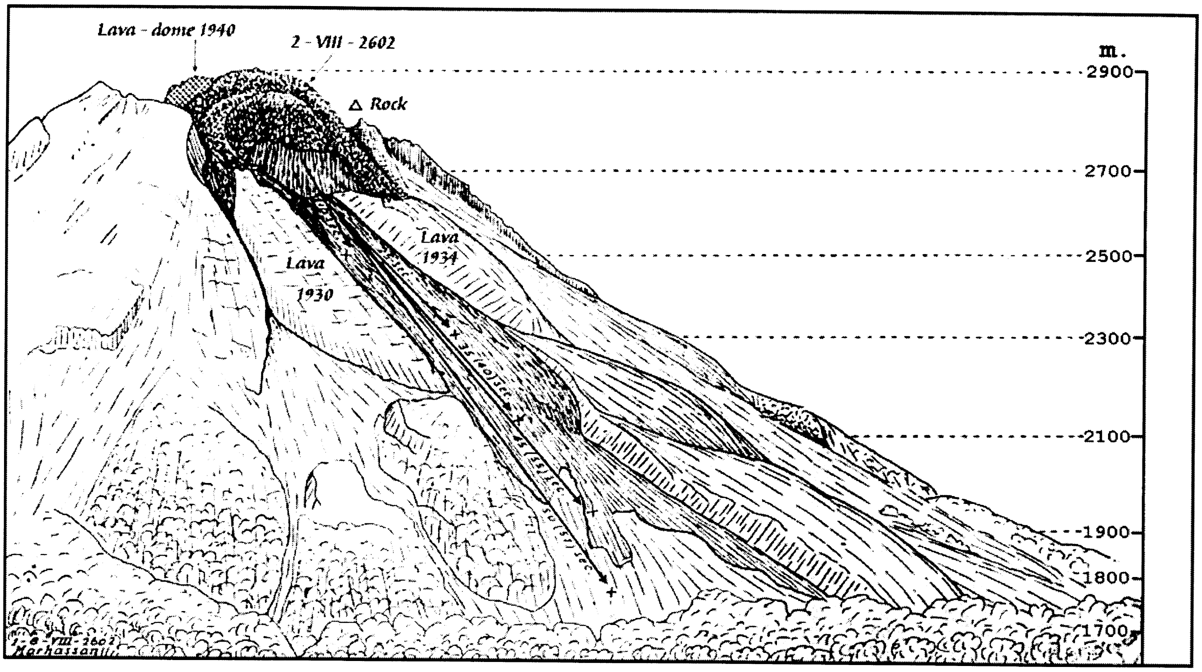


Fig. 25. Merapi from Babadan observation post on the west flank of Merapi on 8 August 1942. Unpublished sketch by Marhassan, VSI files. Fresh collapse zone in front of rim of lava of 2 August 1942, with 1940 dome lava behind. Timed runouts of about 35–50 sec are indicated for rockfalls on the western glide slope, between lavas of 1930 and 1934, that lead toward the Senowo and Blongkeng drainages. Note "Triangle rock" reference point on upper south flank. Observation post location shown on Figs. 1 and 16.

On 18 January 1954, Merapi erupted with a series of nuées ardentes that advanced 5 km in the Apu valley. "Rumblings and detonations" were heard. The type of nuées ardentes could not be distinguished as the volcano was hidden by clouds; an estimated three million m^3 of 1953 dome lava was lost. With the breach 150-m-wide, however, dome collapse involving the axis of the 1953 lava flow seems probable. The total deposit volume (not DRE) was estimated at 11.5 million m^3, suggesting (if correct) that several million m^3 of material were ejected "from the crater pipe." These nuées killed 64 people (30 immediately, 34 from burns after hospitalization) and destroyed at least 3 villages; heavy ash fall destroyed over 90 homes (BVSI, no. 100, Fig. 7). Nuées ardentes of similar size occurred on 20 January, and in the crater breach, fresh dome lava was observed the next day. The eruption was classified as Hartmann B; VEI probably 2 (In a written communication, C. Newhall agrees with this rank, noting the uncertainty of the volume estimate and the probable dome-collapse mechanism). In mid-June, a series of explosions produced ash falls. A large lava flow developed toward the north (Fig. 33a) and dome growth continued into 1955 and filled the breach.

On 3 January 1956, "explosions" were reported to have initiated new activity, but again probably the breach developed by collapse of the central part of the 1954–1955 lava lobe, widening toward the 1948 lava. Avalanches had been heard around 3 a.m., and strong shocks were recorded at Babadan. At 5 a.m. the first "warnings" were given, and an order to evacuate the surroundings of the Apu was issued at 5:58 a.m.; the evacuation was finished by about 8 a.m. Dome-collapse nuées ardentes descended the Apu and ash clouds scorched surrounding terrain (Fig. 31). The main event occurring at 11:25 a.m., and reached a distance of 6 km from the summit. Ashfalls up to 5 cm thick were produced (BVSI, no. 100), some of which caused the collapse of houses, and heavy rains

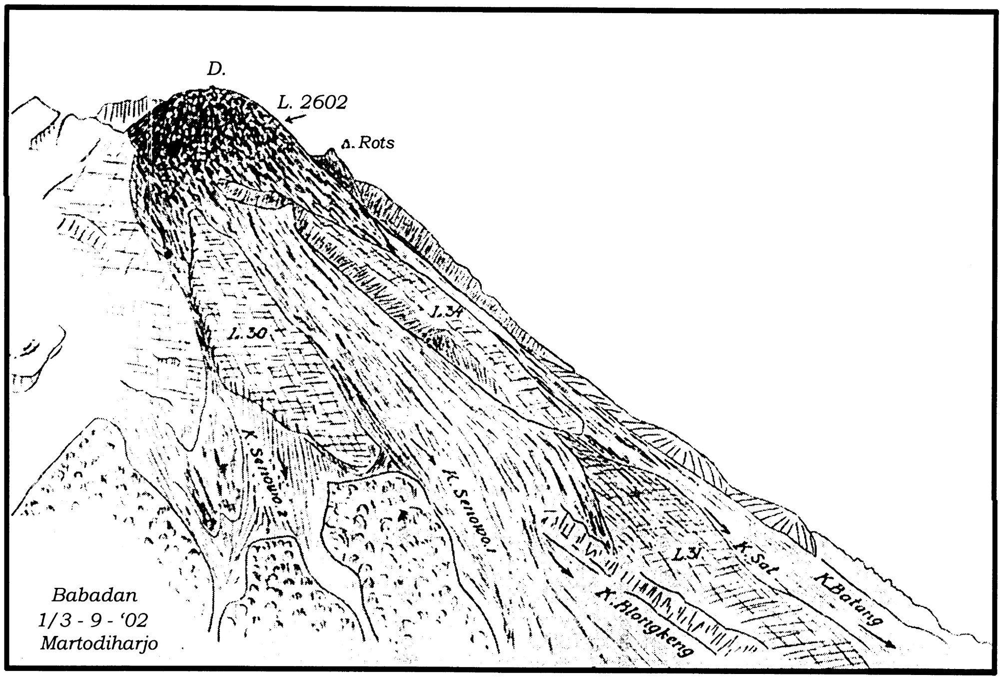


Fig. 26. Merapi from Babadan post on 1–8 September 1942. Unpublished sketch by Martodiharjo. Further growth of the 1942 lava dome fills in the collapse zone shown previously in Fig. 25. Senowo, Blongkeng, Sat, and Batang drainages are identified. "Triangle rock" is reference point.

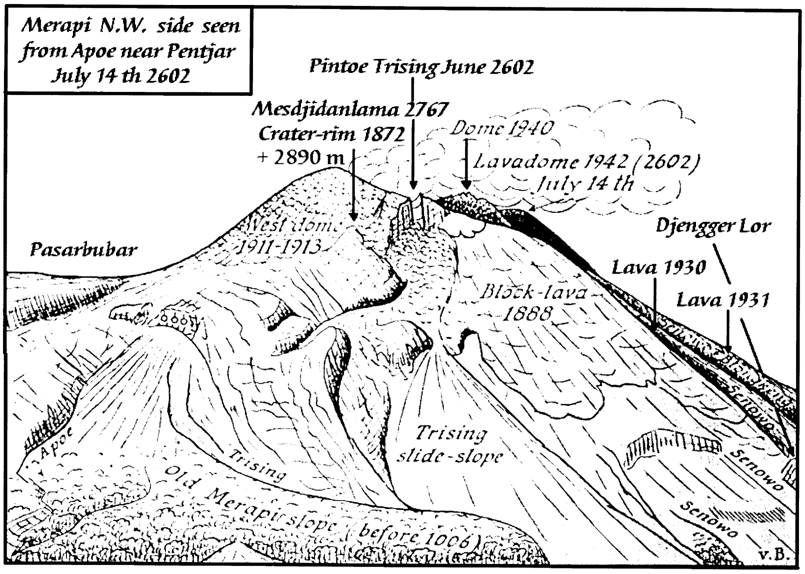


Fig. 27. Merapi from the northwest, on 14 July 1942. Unpublished sketch by Van Bemmelen. Note 1942 lava, west of Dome 1940, and positions of West Dome, Mesdjidanlama, crater rim of 1872, Trising breach of June 1942, surficial lavas of various ages. Age assigned to Old Merapi slope, "before 1006 A.D.", refers to an interpretation now discredited (see Newhall et al., 2000 – this volume).

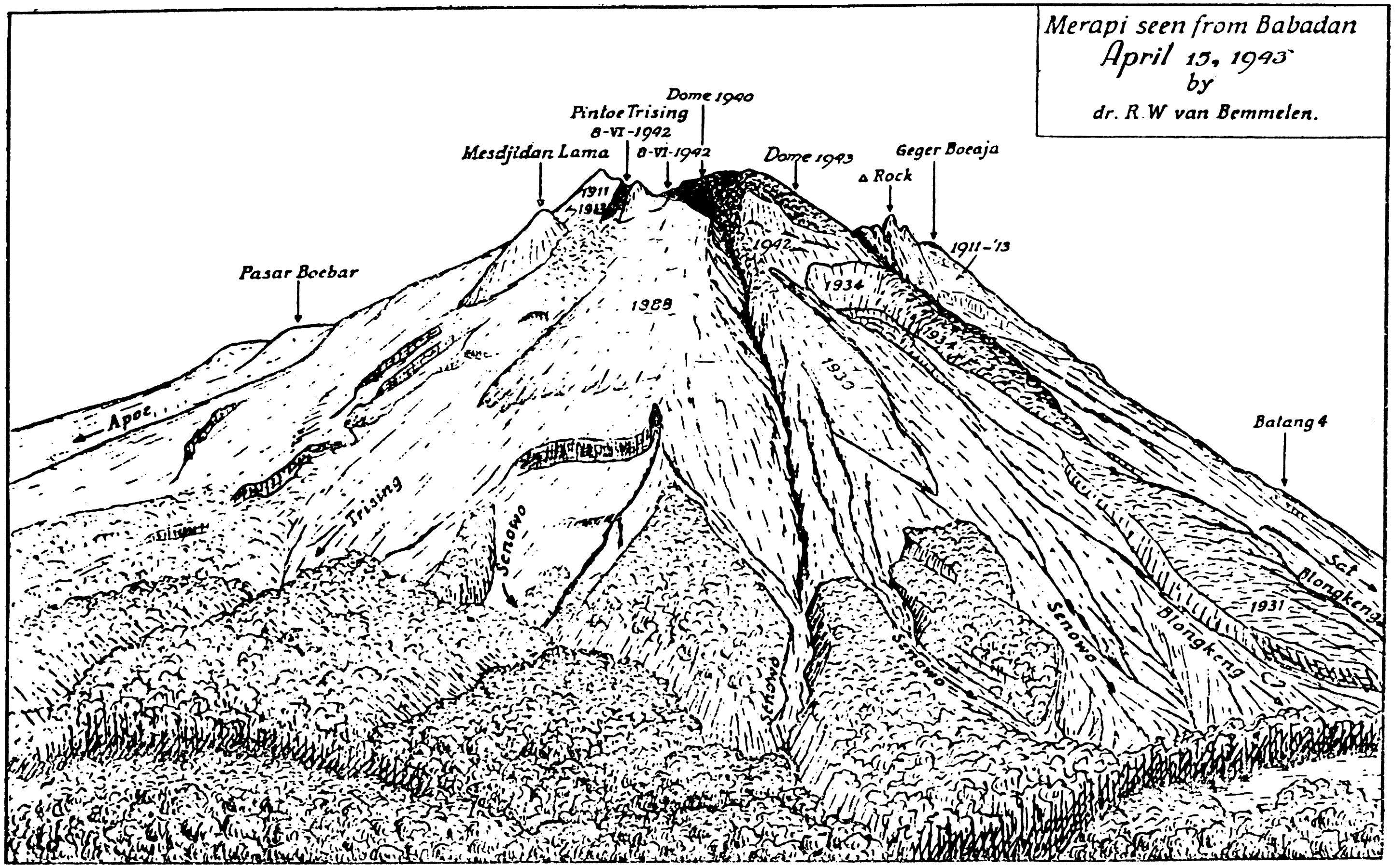


Fig. 28. Merapi from near Babadan post, on 15 April 1943 (after Van Bemmelen, 1949). Note Trising breach (*Pintoe Trising*) of June 8, 1942. Reference points include Mesdjidanlama, “Triangle rock.” Surficial lava ages as noted, including those from West Dome (1911–1913).

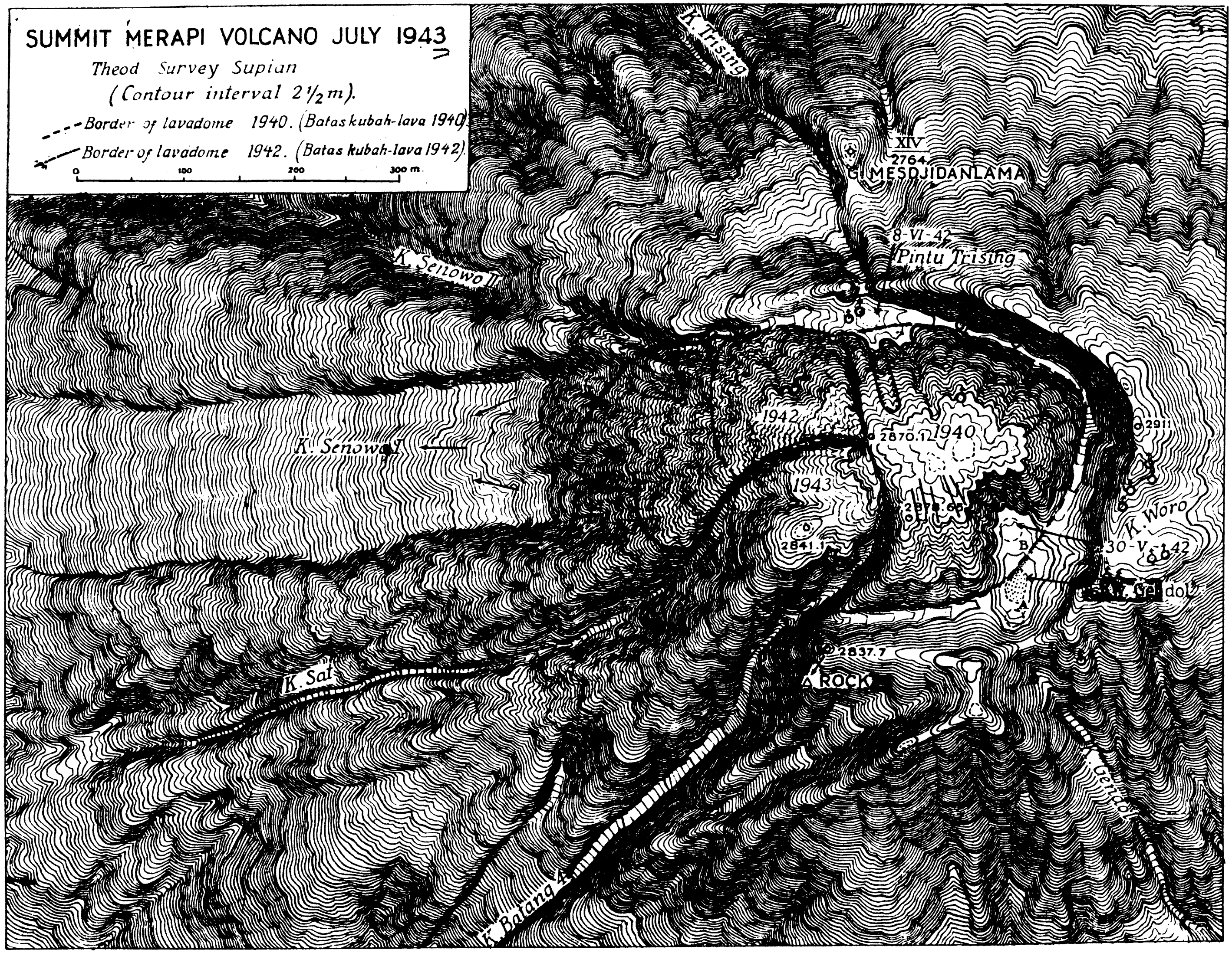


Fig. 29. Topographic survey of Merapi summit during July 1943. Unpublished map, VSI archives. Legend: border of 1940 lava, dashed line; border of 1942 lava, dash-dot line. The 1943 lava emerges from a vent near the summit contact of 1940 and 1942 lavas, and flows toward the southwest. Fumaroles indicated by circles with arrows. Note explosion sites for 30 May, and 8 June 1942 (cf., Fig. 23). Reference points include "Triangle rock", G. Mesdjidanlama.

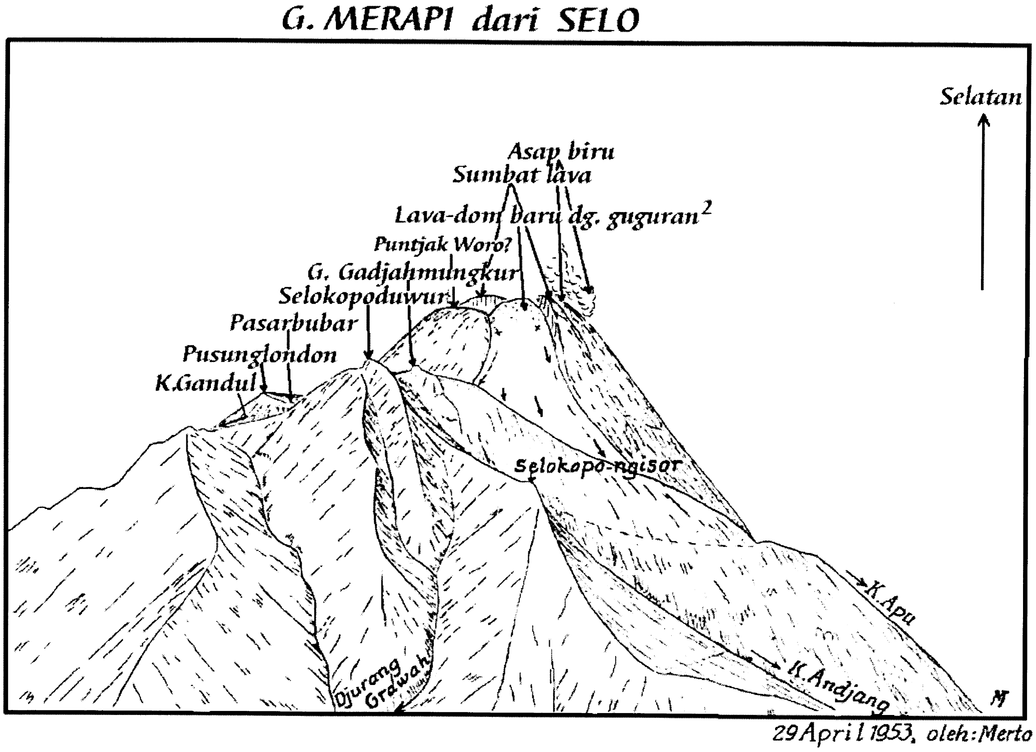


Fig. 30. Merapi viewed from Selo village on the north on 29 April 1953. Unpublished sketch by Merto. Note active lava lobe with block avalanches (*guguran*), summit location of Woro, Selokopoduwur, Pasarbubar, Pusunglondon, G. Gadjahmungkur, other features. Note slight changes in spelling of place names, compared to earlier figures. Compare with photographs of Fig. 12, and Fig. 8.

on ash formed a "cold" lahar in the Senowo. A new flow of lava then emerged after 6 January (Fig. 31), grew, and filled the breach. Details of distributions of lava flows are shown by a series of excellent scale models in the VSI (MVO) museum in Yogyakarta.

1957–1960: In 1957, fresh lava erupted in the upper Batang breach and covered lava of 1931 and 1934 (BVSI, no. 101). Collapse-type nuées reached 4 km from the crater rim. In 1957 and 1958, rockfalls occurred toward the Sat and Senowo drainages, with the number of rockfalls decreasing between July and December 1958 (Fig. 32).

In 1958, a topographical theodolite survey of the summit was completed, the first since 1943 (BVSI, no. 102). Whereas the crater rim in 1943 had a horse-shoe shape and was open to the west, by 1958 only the south and east crater rim remained and the north rim was covered by lavas extruded in 1948 and 1953–1958 (Fig. 33). About 50 m separated the south rim from the lava dome. Hartmann A; VEI 1. A Weichert mechanical seismograph was installed in 1959. In 1960, observations at the summit were carried out monthly, but no important changes were observed (BVSI, no. 103). No effusive activity occurred, but minor rockfalls were produced from disintegration of the 1957 lava tongue (Figs. 29 and 30). Also in 1960, Suryo proposed to the government an extension of the forbidden zone, because of the tendency of activity to shift toward the southwest; the previous hazard map had been issued by Van Bemmelen in 1941 (BVSI, no. 104). These new boundaries were "tested" in 1961 (Fig. 31).

1961: After about 2 years of quiescence, activity resumed on 19 March with noises of avalanches from the cloud-shrouded summit (BVSI, no. 104). On 11 April, incandescence indicated fresh lava venting through 1957 lava, and two days later 18 dome-collapse nuées rolled down the Batang to distances of

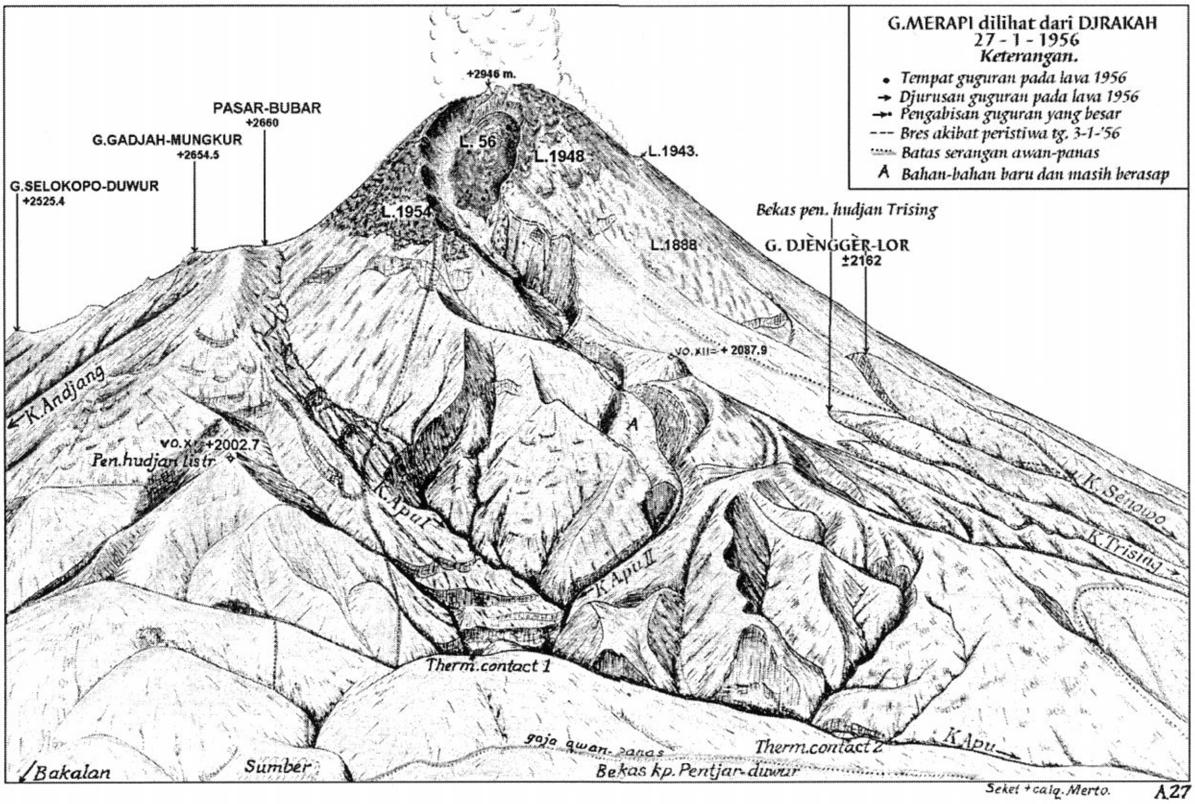


Fig. 31. Merapi viewed from Djrakah observation post on the north on 27 January 1956. Unpublished sketch by Merto. Reference points include G. Selokopo-duwur, G. Gadjah-mungkur, Pasar-bubar, and G. Djengger-lor (north). Active lobe of lava 1956 between lavas of 1948 and 1954; breach developed near the contact of these lavas on 3 January 1956, with the collapse generating a large nuée ardente. Legend: sources for rockfalls in 1956 lava, dots; directions taken by these rockfalls, arrows; main channel of coarse debris in collapse of 3 January, dashed line; boundary of region affected by nuée ardente, dotted line.

3.5 km, accompanied by ash-cloud fallout. The frequency of rockfalls and nuées increased to >100 nuées on 17 April, the largest of which swept 6 km down the Batang. On this day, a second point of active avalanching developed through the 1957 lava dome, where avalanches and nuées descended in the Senowo and a lahar was mobilized by interaction with water. On 18 April, a large nuée extended 6.5 km along the Batang and destroyed part of Gendeng village (Fig. 34). Warnings had been issued after 13 April, and after 18 April, depending on sector, communities in the forbidden zone were evacuated and others placed on a state of alert (BVSI, no. 104).

On 20 April, an ash cloud accompanied by lightning rose 1000 m above the crater near Batang breach, as nuées ardentes, interpreted to be "explosion type" (BVSI, no. 104) destroyed Gendeng village (Fig. 34). In the following week, new lava effused, together with the occurrence of nuées of several types. On 7 May, rhythmic jets of incandescent lava rose to 150 m above the vent near the Batang breach, and larger explosions, with plumes rising as high as 3 km above the crater, produced fountain-collapse nuées ardentes in the Batang (with runout to 3.5 km), and simultaneously in the Senowo, Woro and Gendol (Fig. 34). Continuous roaring ("the sound of a blower") was reported on a number of occasions, and "the sound of continuously descending nuées ardentes was comparable to the sound of a lahar flow during thunder storm (sic)." On 8 May, a dense pulsating black ash plume "rose from an eruption hole in the 1957 lava," and generated, by 10:17 a.m., 17 nuées ardentes that

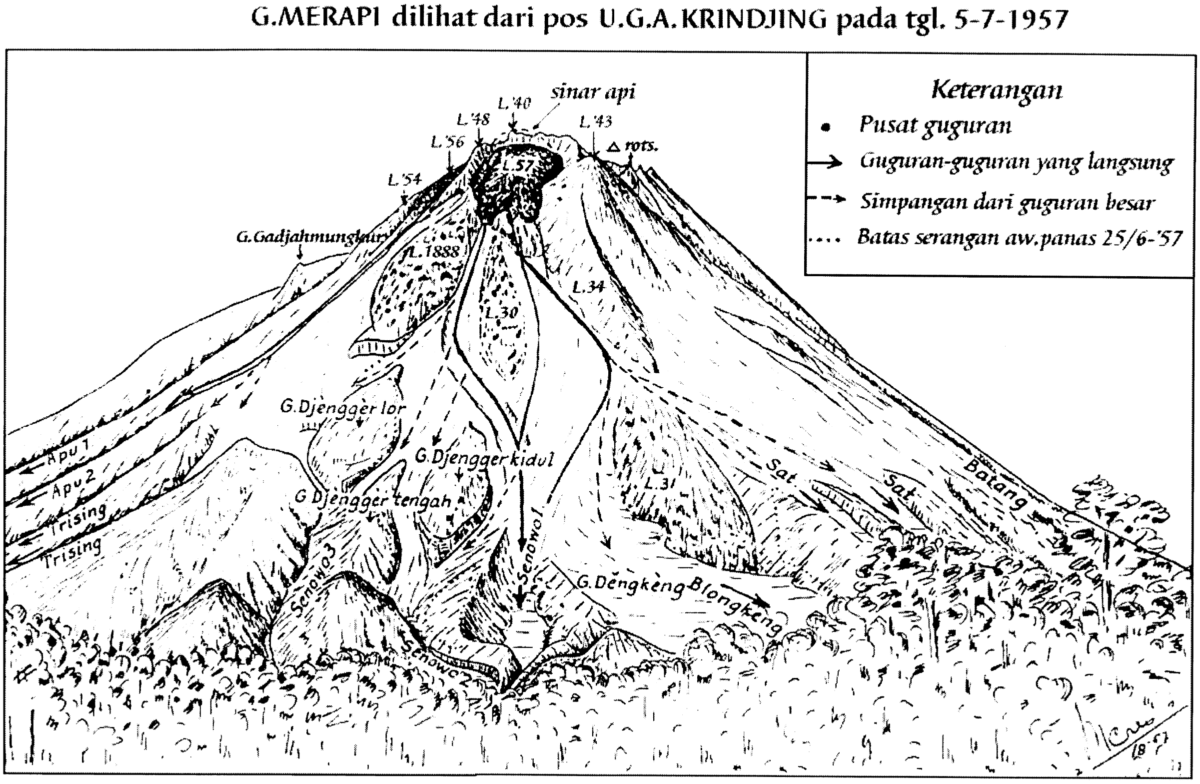


Fig. 32. Merapi viewed from the west on 5 July 1957. Unpublished sketch by Merto. Note "recent" lavas of 1954, 1956, 1957. Also note reference location of G. Gadjahmungkur, compared to Fig. 30. Other locations include G. Djengger North (*lor*), South (*kidul*), and Middle (*tengah*), G. Dengkeng, and "Triangle rock". Lavas of different ages noted as "L." with year (e.g., L.'34 indicates Lava 1934). River drainages identified on lower slopes. Legend: source of rockfalls (*guguran*), dots; rockfall paths, solid lines with arrow; supplementary paths for large rockfalls, dashed lines with arrow; boundary of nuée ardente of June 25, 1956, dotted line. Glowing summit area (*sinar api*) indicated by dashed line. Observer location is Krindjing (Fig. 37).

reached as far as 7 km on the Batang. The paroxysm occurred around 3 p.m. when "the gas phase reached its maximum," lasted about 30 min and generated nuées ardentes to 12 km length in the Batang, to within 1 km of the Ngepos observatory post (Fig. 34). "Although the people were evacuated long before the paroxism (sic)…casualties could not be avoided. There were always a few people returning to their houses during the day time, in spite of the repeated warning by the Volcanological Survey" (BVSI, no. 104); thus 12 persons were trapped by a nuée during the paroxysm on 8 May, with six killed and the other 6 severely injured. A broad ash cloud extended to the Indian Ocean over a 160-km length of shoreline (BVSI, no. 104, Fig. 8).

The paroxysm on 8 May created a depression on the southwest part of the summit, and the Batang breach was widened. An important effusive phase followed and produced a lava tongue accompanied by swarm seismicity (Fig. 35); the lava flux was about 200,000 m^3/day in June. Rockfalls were frequent but diminished in July, and effusive activity lasted until 27–28 November when 90% of the dome was destroyed by a succession of 119 dome-collapse nuées (Fig. 36), with the nuées reaching as far as 8 km in the Batang. The collapses may have been triggered by pressurized steam and explosions related to torrential rainfall on the hot lava. No new effusion of lava was noted after the dome collapse, and only minor activity followed in the next 5 years. Hartmann B, noting the extensive forephase activity preceding fountain-collapse nuées; VEI 3. The total volume of eruptive products was estimated as 42 million m^3 (BVSI, no. 104), with the DRE volume perhaps about 30 million m^3; however, much of this volume may have represented older material.

Seismicity of “a special type, resembling the Showa Shinzan earthquake swarms during the 1944 Usu eruptions in Hokkaido described by Minakami,” was observed in 1960 and 1961, with seismic events having “all the same shape” and a duration of about 8 sec (BVSI, no. 104). However, the seismographs were of low sensitivity, and recording at improved sensitivity was impeded by lack of electricity at observatory posts.

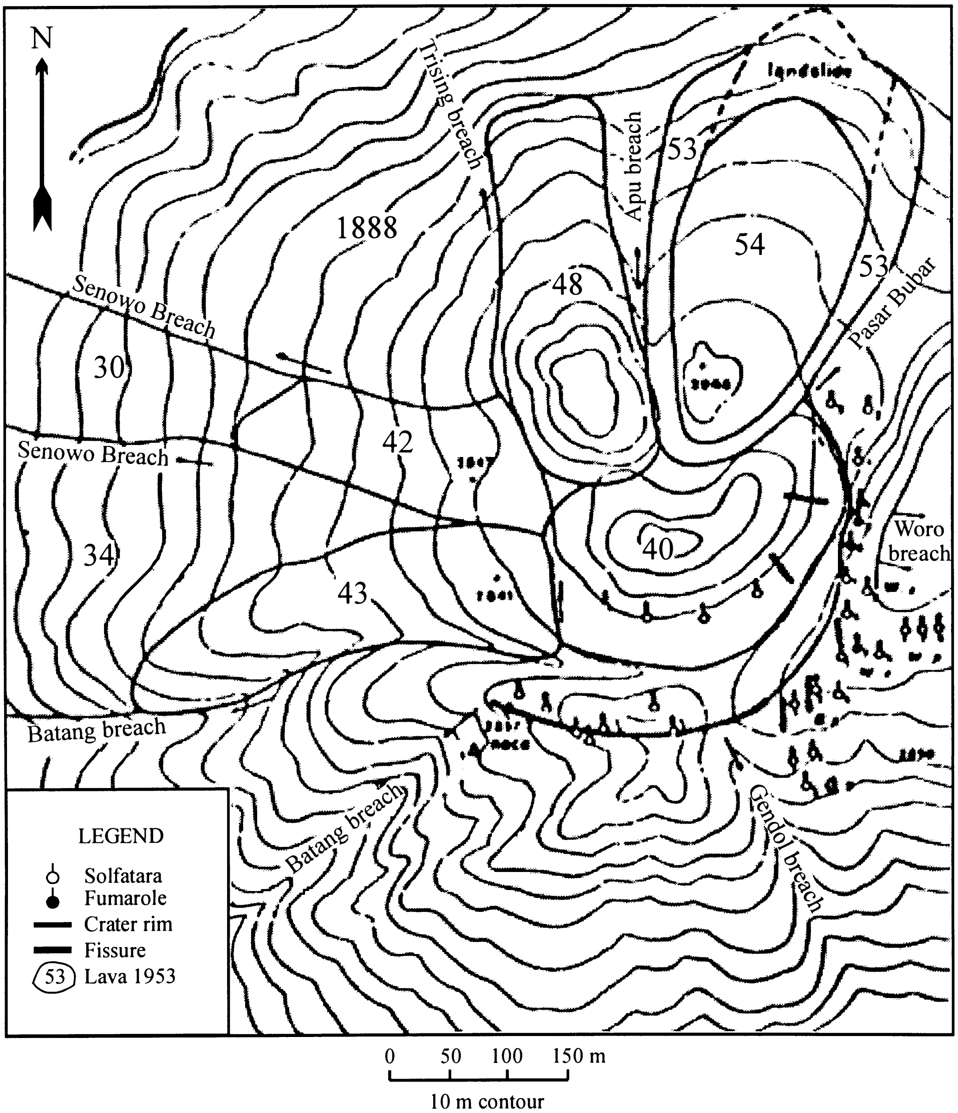
1962–1966: Rock avalanches and minor lahars were reported, but with no new effusive activity (BVSI, no. 104). In October 1962 a heavy rain mobilized debris from the 1961 eruption, forming a large lahar on the Bebeng that swept through 5 villages, killing 2 persons and injuring 5; other inhabitants were alarmed by the roaring noise of the oncoming lahar, and escaped. In December 1963, the railroad between Yogyakarta and Magelang was damaged near Muntilan by a lahar in the Blongkeng. This same lahar also destroyed an orphanage in Muntilan, which fortunately had been evacuated before the lahar struck (BVSI, no. 104).

A summit topographic map was made in 1962 (BVSI, no. 104). Gas emissions were reported in 1965 and 1966, and a few rockfalls of old material moved toward the Batang valley (BVSI, no. 106).

1967–1969: After quiescence since 1961, a new eruption episode started on 12 January 1967, with an explosion that was heard but not witnessed because of poor visibility; another explosive eruption occurred two days later (BVSI, no. 106). It was assumed that no juvenile material was produced in these gas-blast, vent-clearing events. Precursory phenomena were unclear, but a few volcanic earthquakes had been recorded a month earlier in Kaliurang. During February through April, incandescence was observed at several locations, and hot rockfalls, and some nuées, rolled down from these points towards the Batang. Dome growth began 11 April. Volcanic seismicity increased after August, peaked in September but remained high (Siswowidjoyo, 1984; BVSI, no. 106) until the paroxysm on 7–9 October 1967, which produced 39 nuées. Volcanic earthquakes then declined sharply. The largest nuée reached 7 km in the Batang (Fig. 37). A large portion of the 1967 lava dome had collapsed, and part of the Geger Buaya ridge, on the upper south flank, was eroded on the northwest side (Fig. 38). Fresh lava effused in October and a new dome-coulée formed.

In 1968, activity continued with numerous rockfalls and occasional nuées, 2–19 per month and chiefly in the Batang, along with seismicity of different types. The dome grew to about six million m^3 in volume, and the nuées reached to 2.8 km. Activity then waned in August and September, at a time when modern seismic monitoring and event classification were initiated by Japanese scientists (Shimozuru et al., 1969). I. Suryo ranked the eruption as Hartmann B (BVSI, no. 106), VEI 2. Activity resumed in October 1968, and BVSI (no. 106) suggests that the new activity in October overlapped the “unfinished” end phase of the earlier activity, without a clear intervening period of quiescence.

An earthquake swarm occurred in mid-December, peaked at 1500 “multiphase”-type events (Shimozuru et al., 1969) and then declined before the eruption on 7–8 January 1969. The eruption was accompanied by a series of nuées ardentes, advancing 3 km, then 6 km, then 13.5 km down the Bebeng, and also as much as 8 or 9 km along the Batang, Krasak, and Blongkeng, burning several villages (Fig. 39). Most nuées were considered as dome-collapse type, but as the eruption clouds rose several km above the crater, some of the largest nuées were described as “eruption-type” (BVSI, no. 106). C. Newhall (written communication) observed that deposits tentatively believed to represent 1969 nuées contain numerous breadcrust bombs, and thus represent explosion events. The villages had been evacuated as a result of the seismic swarm, and only one death was reported. The 1967–1968 dome was reported to have collapsed (Hadikusumo, 1969; Shimozuru et al., 1969). A tephra plume rising as high as 4 km over the summit deposited ash over a broad area extending to Magelang (Fig. 40). By 9 January 1969, a new dome began to emerge, flowing 400 m west (BVSI, no. 106). Numerous lahars, which formed in the rainy season from remobilized nuée and fallout deposits, destroyed 23 villages and 742 homes and caused some casualties (Fig. 39). Photos by Minakami et al. (1969) compare 1968 Merapi with earlier views (Fig. 12). Hartmann B; VEI 2. The



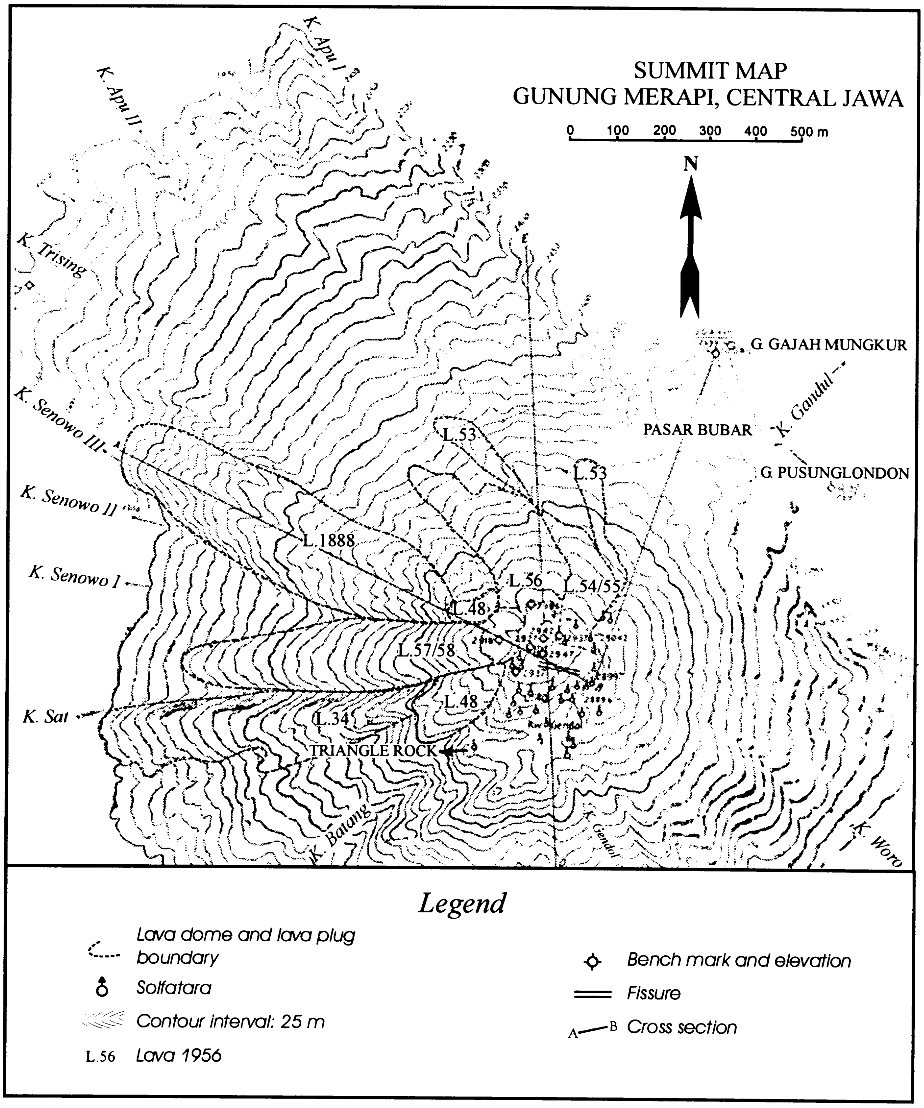
(a)

Fig. 33. Maps of the Merapi summit. a. Map showing distribution of lava flows to 1954 (BVSI, no. 100). b. Map surveyed 1955–1958 (BVSI, no. 102). First survey since 1943. Reference points include G. Gadjahmungkur, "Triangle rock," Gendol, river drainages on lower slope. Lava ages noted as "L." with year (L. 56 indicates Lava 1956, etc.). Legend: Lava dome or flow boundary, solid (a) or dashed (b) line; solfatara, circle with arrow; fumarole (dot with tickmark); benchmark with elevation, crossed circle; fissure, double-line. Maps are original with some revision of labels to aid legibility.

VEI ranking is based on unconfirmed volume estimates (Fig. 45).

1970–1971: Sporadic minor rockfalls occurred during 1970 from localized collapses of the 1969 dome lava (BVSI, no. 106; Hadikusumo, 1969). Apart from this, the volcano was inactive (Siswowidjoyo and Harjowarsito, 1974).

1972–1974: Renewed activity began 6 October

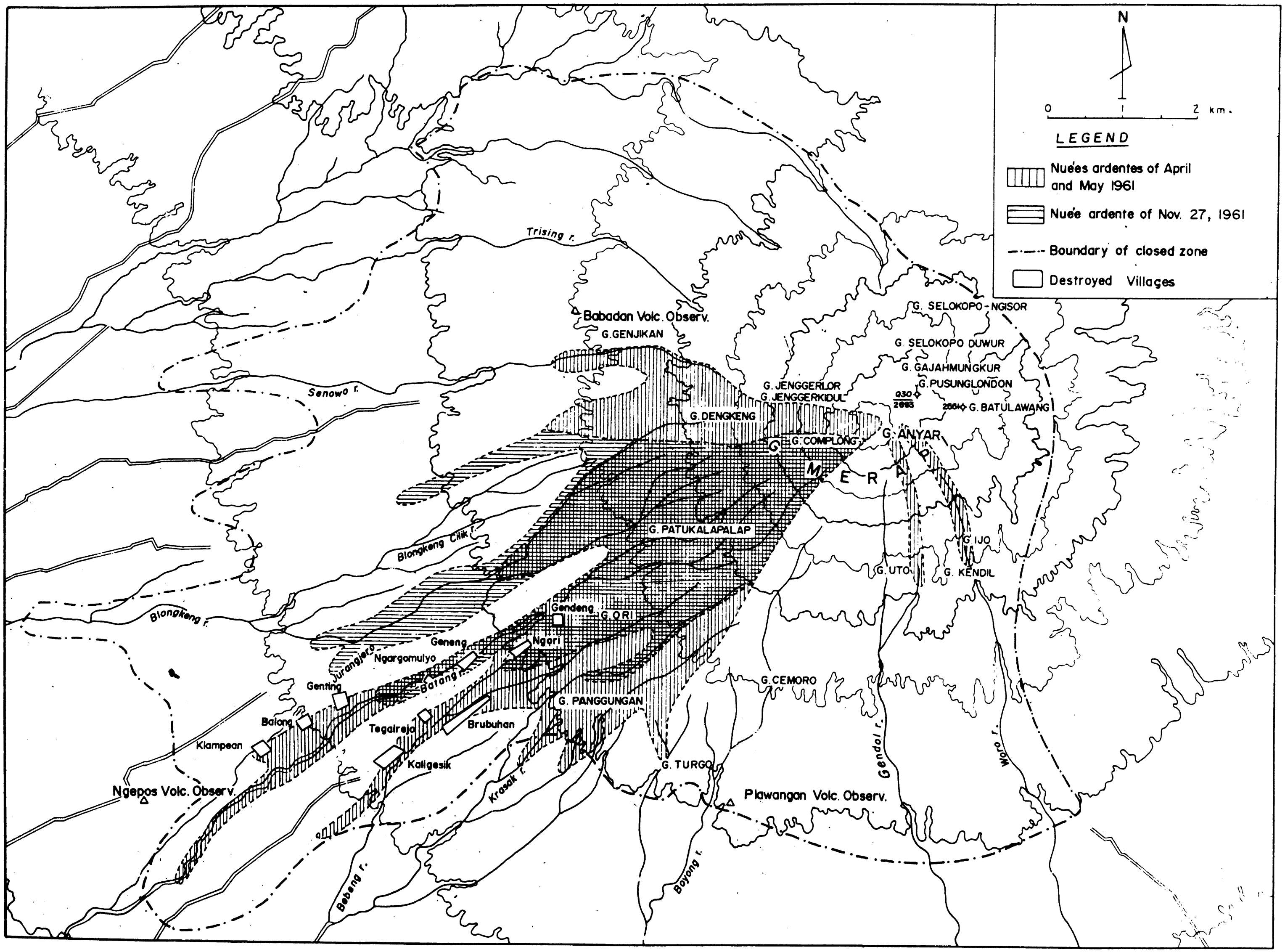


(b)

Fig. 33. (*continued*)

1972 (Siswowidjoyo and Harjowarsito, 1974; Siswowidjoyo, 1984), with an explosion centered between the 1969 and 1961 lavas in the upper Batang sector of the summit that created a black ash-plume with lightning. Fountain-collapse nuées ardentes invaded the Batang for 3 km, and a few mm of ash fell at Babadan. The explosion produced a small circular crater on the 1969 dome.

On 13 December 1972, a new explosion produced an ash plume 700 m high, with fallout extending to 7.5 km from the summit. Similar explosions occurred in January and February of 1973. In April, glowing lava rose in the October 1972 crater accompanied by multiphase-type seismicity, and slow effusion continued to May until almost all of lava 1969 was covered. Relatively deep earthquakes were recorded in late


N
0 1 2 km.
LEGEND
Nuées ardentes of April and May 1961
Nuée ardente of Nov. 27, 1961
Boundary of closed zone
Destroyed Villages
Trising r.
Babadan Volc. Observ.
G. GENJIKAN
G. SELOKOPO-NGISOR
G. SELOKOPO DUWUR
G. GAJAHMUNGKUR
G. PUSUNGLONDON
G. BATULAWANG
G. JENGGERLOR
G. JENGGERKIDUL
G. DENGKENG
G. COMPLONG
G. ANYAR
Senowo r.
M E R A
G. PATUKALAPALAP
Blongkeng Cilik r.
G. IJO
G. UTO
G. KENDIL
Blongkeng r.
Gendeng
G. ORI
Geneng
Ngori
Jurangjero
Ngargomulyo
Genting
Batang r.
Balong
Tegalreja
Brubuhan
G. PANGGUNGAN
G. CEMORO
Klampean
Kaligesik
Krasak r.
G. TURGO
Gendol r.
Woro r.
Ngepos Volc. Observ.
Plawangan Volc. Observ.
Bebeng r.
Boyong r.

May. On 20 September 1973, a dome-collapse nuée descended the Batang valley for 6 km, and lava effusion resumed. On 19 December, a new explosive phase generated nuées ardentes that extended to 7 km down the Bebeng and 5.5 km down the Batang and Blongkeng (Fig. 41). The rainy season produced significant lahars. This eruption episode ended in September 1974. Hartmann B; VEI 2.

1976–1979: According to Siswowidjoyo (1984), 1976 began a period of activity that lasted through 1979 (Fig. 42). On 5 March, with minor precursory seismicity, rockfalls and gaseous plumes were observed. On 6 and 12 March, nuées ardentes descended the Batang, Blongkeng, and Bebeng valleys as far as 6 km. Dome growth continued, and by June 1976, 0.9 million m^3 of lava had been extruded; by the end of 1977, the volume reached 2.4 million m^3. Dome growth was accompanied by sporadic rockfalls and multiphase earthquakes. In January 1978, a collapse of a section of the 1976 crater and partial destruction of the dome took place because of a series of explosions (Siswowidjoyo, 1984). A new dome began to form over the remains of the 1967 and 1973 domes, and descended as a lava tongue to the southwest (Fig. 42). In August, a dome-collapse nuée reached 6 km. By November, the dome volume was 1.1 million m^3, and the extrusion rate was 100,000 m^3/month. Rockfalls continued until December 1979, when activity stopped. Hartmann B; VEI 2.

During this period, investigations of fumaroles were initiated by French scientists, involving studies of sublimates, gas chemistry and isotopic compositions (Allard and Tazieff, 1979; LeGuern and Bernard, 1982; LeGuern et al., 1982), and this monitoring was continued in subsequent decades.

1980–1984: The next episode began around May 1980 (Siswowidjoyo, 1984). Dome growth continued to 29 November–2 December 1981, when about 60% of the dome collapsed (Fig. 42). Effusion was then very slow until June 1982. Heavy ashfall in February damaged crops and halted traffic in the nearby Bojolali region (SEAN, 1989). On 22 and 23 November 1982, collapse of dome lava, possibly followed by a gas explosion, led to nuées ardentes that travelled as far as 8.4 km. VEI 2. The remnant dome lava was 0.5 million m^3, compared with 1.7 million m^3 before the collapse. In late December, new lava emerged, with weak tremor and multiphase seismicity accompanying dome growth that continued to March 1983. In 1982, a modern seismic network was installed by USGS-VSI scientists, for the first time enabling determination of hypocenter locations.

Dome growth continued and, by May 1983, the new lava volume was 0.4 million m^3 (Siswowidjoyo, 1984). By August, this new lava had completely covered the old dome, and the combined volume of the two dome lavas was 1.2 million m^3. A collapse of the composite lava dome occurred on 5 October, and lava effusion continued at a slow rate.

On 27 May, volcano-tectonic earthquakes were recorded by the seismic network. The number of these events increased on 5 June, and again on 11 June. With the dome volume at 3.6 million m^3, nuées ardentes occurred on 13 June, but this activity ceased by noon the next day. At 02:15 a.m. on 15 June 1984, a strong explosion occurred (Team Merapi, 1984; Ratdomopurbo and Poupinet, 2000 – this volume). Nuées ardentes extended 5–7 km down the Batang, Bebeng, Putih and Krasak valleys. These nuée deposits have been studied by Boudon et al. (1993). The eruption plume rose to 6 km, causing widespread ashfall that extended 80 km northwest to the 1-mm isopach (Team Merapi, 1984). Additional explosions occurred at 03:47 and 06:00, and activity continued with small nuées and glowing rockfalls. By nightfall of 15 June, it was confirmed that the crater had been emptied of post-1979 dome lava. Hartmann B; VEI 2.

1984–1991: The 15 June 1984, explosions were followed by rapid, then waning, dome growth. Dome volume reached about 2.8 million m^3 by December 1984, and growth continued through March 1985. On 10 October, 1986, and for the next 5 days, the dome was partially destroyed by a series of

Fig. 34. Original map of Merapi showing areas affected by nuées ardentes in 1961 (BVSI, no. 104). Legend: nuées ardentes of April and May, 1961, vertical lined pattern; nuée ardente of 27 November, 1961, horizontal lined pattern; "forbidden-zone" boundary, dash-dot line; destroyed village, unshaded block. Boundary of forbidden-zone was revised in 1960 from the previous hazard map of 1941 (BNEIVS, no. 95–98). Compare this zonation to nuée ardente boundaries, and villages destroyed, in 1961. Also note, nuée ardente deposit lobes in Gendol and Woro drainages, in April–May 1961. Plawangan, Ngepos, and Babadan observatory posts indicated by triangles.

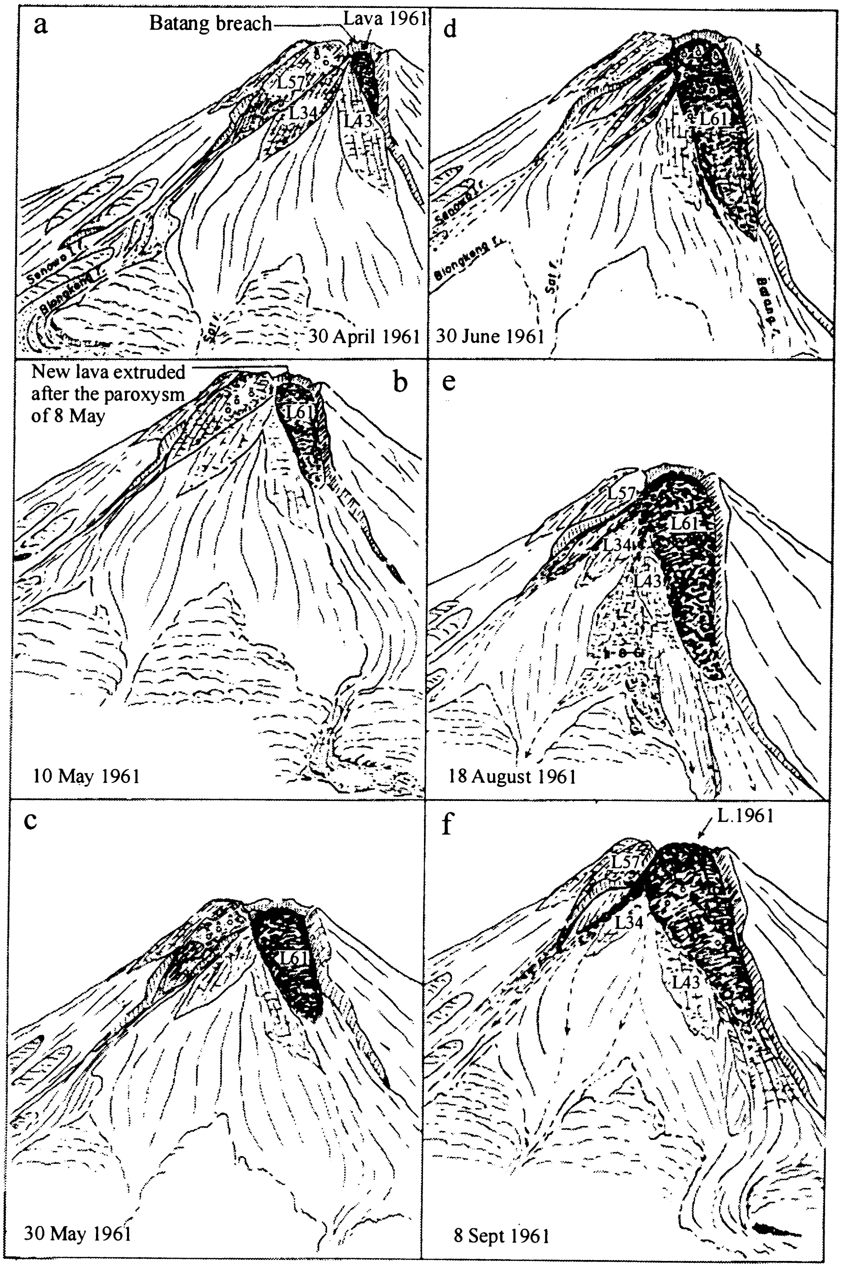


Fig. 35. Original sketches of Merapi from Ngepos post on the southwest flank (see Fig. 34) from 30 April to 8 September 1961 (BVSI, no. 104). a. 30 April 1961; lava tongue of 1961 growing over 1943 lava in Batang breach. b. 10 May; new lava extruded after "paroxysm" of 8 May. c. 30 May, showing further growth. d, e, f. Continued growth to June 30, 18 August, and 8 September, respectively.

nuées ardentes that may have been prompted by strong summit rains. No seismic precursors were recognized. Dome growth resumed at an average rate of 15,000 m^3 per day to February 1987, after which only the upper part of the dome grew. Dome volume was six million m^3 by September 1988, and 6.8 million m^3 by November 1991. Hartmann A; VEI 2.

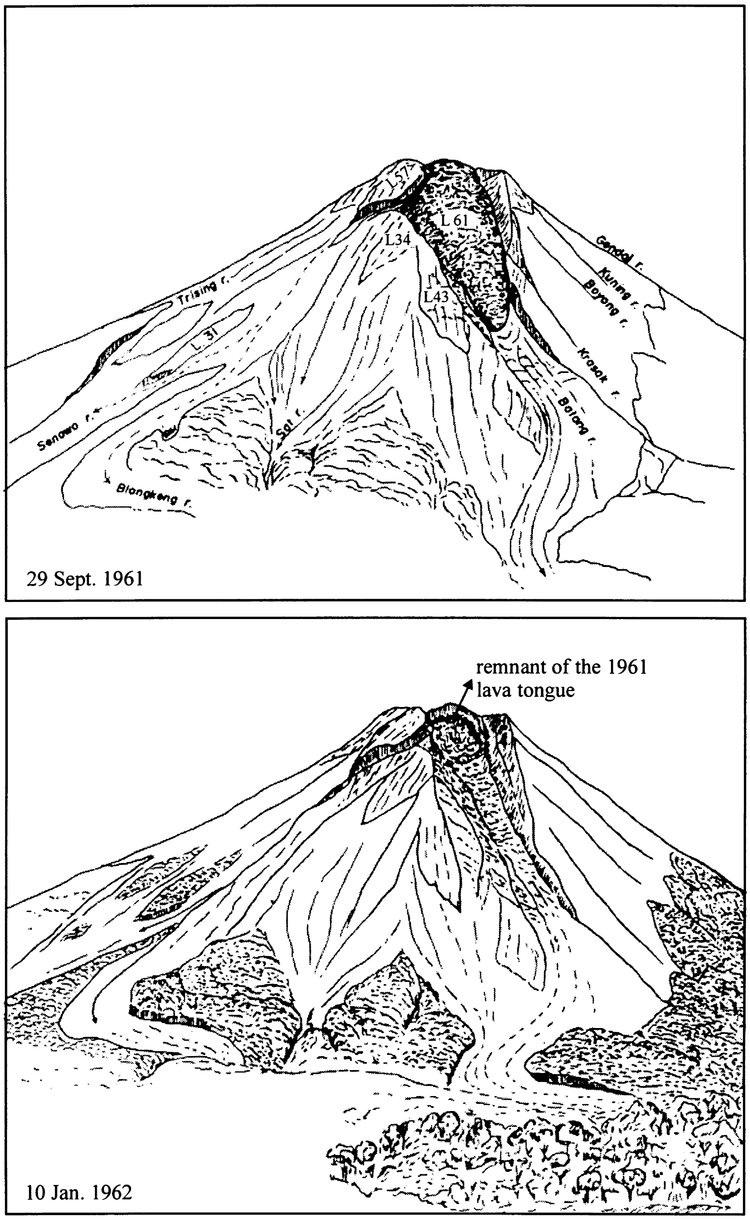


Fig. 36. Original sketches of Merapi from Ngepos post, comparing views from (a) 29 September 1961 to (b) 10 January 1962 (BVSI, no. 104; cf. Fig. 35f). Sketch shows views before and after piecemeal collapse of nearly all of 1961 lava tongue in November 1961. A small remnant of 1961 lava is shown in (b). Hundreds of nuées ardentes were generated, with runout as far as 8 km.

However in 1990, a clear buildup of seismicity was recognized, culminating with a swarm of about 200 large shallow volcano-tectonic events that accompanied a gas outburst in August, with a 1000-m plume (Ratdomopurbo and Poupinet, 2000 – this volume). A variety of volcano-tectonic and low-frequency earthquakes and tremor occurred in 1991, and the seismicity peaked in September. Summit and flank geodetic networks had been reoccupied since 1988, and these measurements revealed accelerating

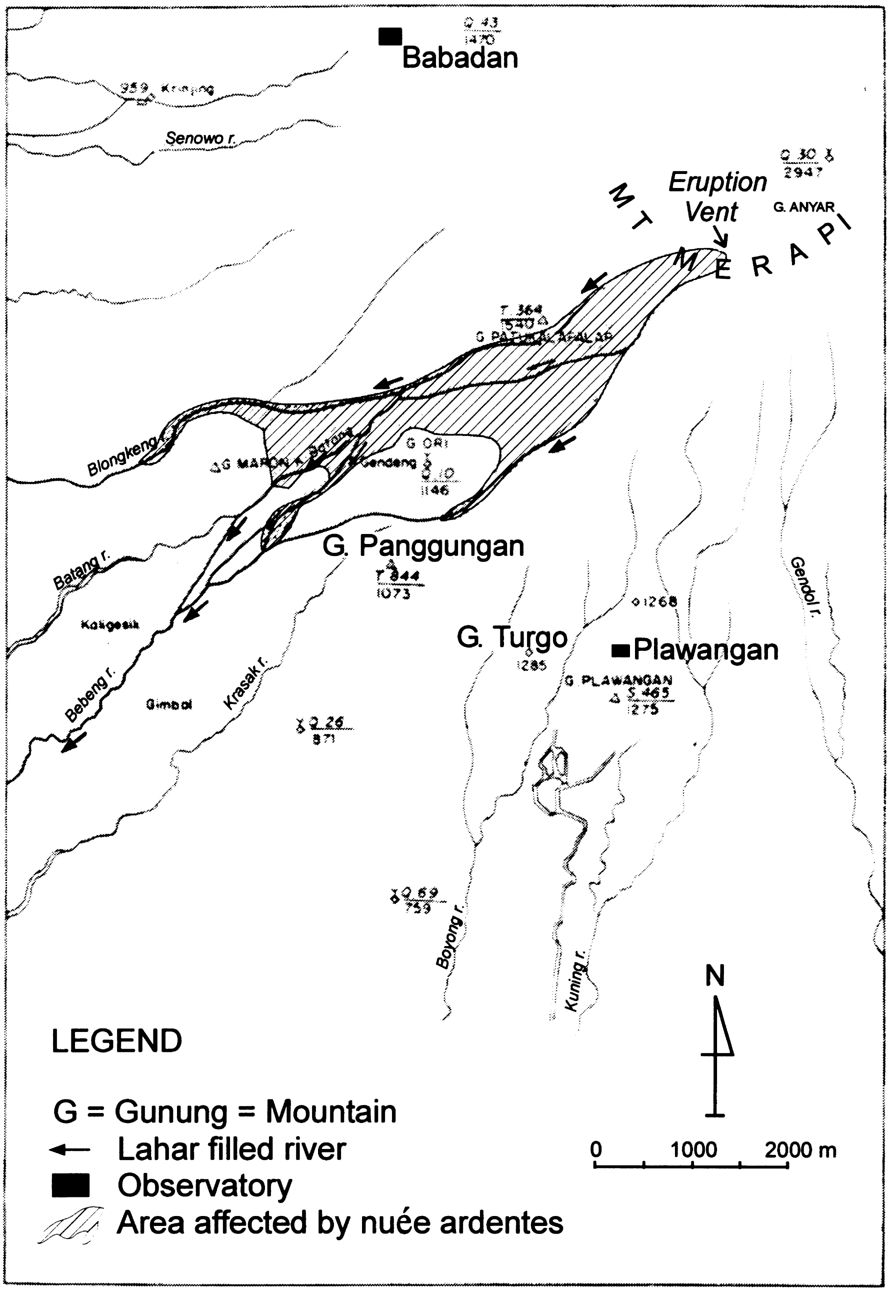


Fig. 37. Original sketch of southwest flank of Merapi affected by nuées ardentes on 7–9 October 1967 (BVSI, no. 106). Legend: G. (Gunung, mountain) denotes local reference points such as G. Maron, G. Panggungan, G. Turgo; Lahar-filled rivers shown by arrows; October 1967 nuée ardente deposits indicated by lined pattern.

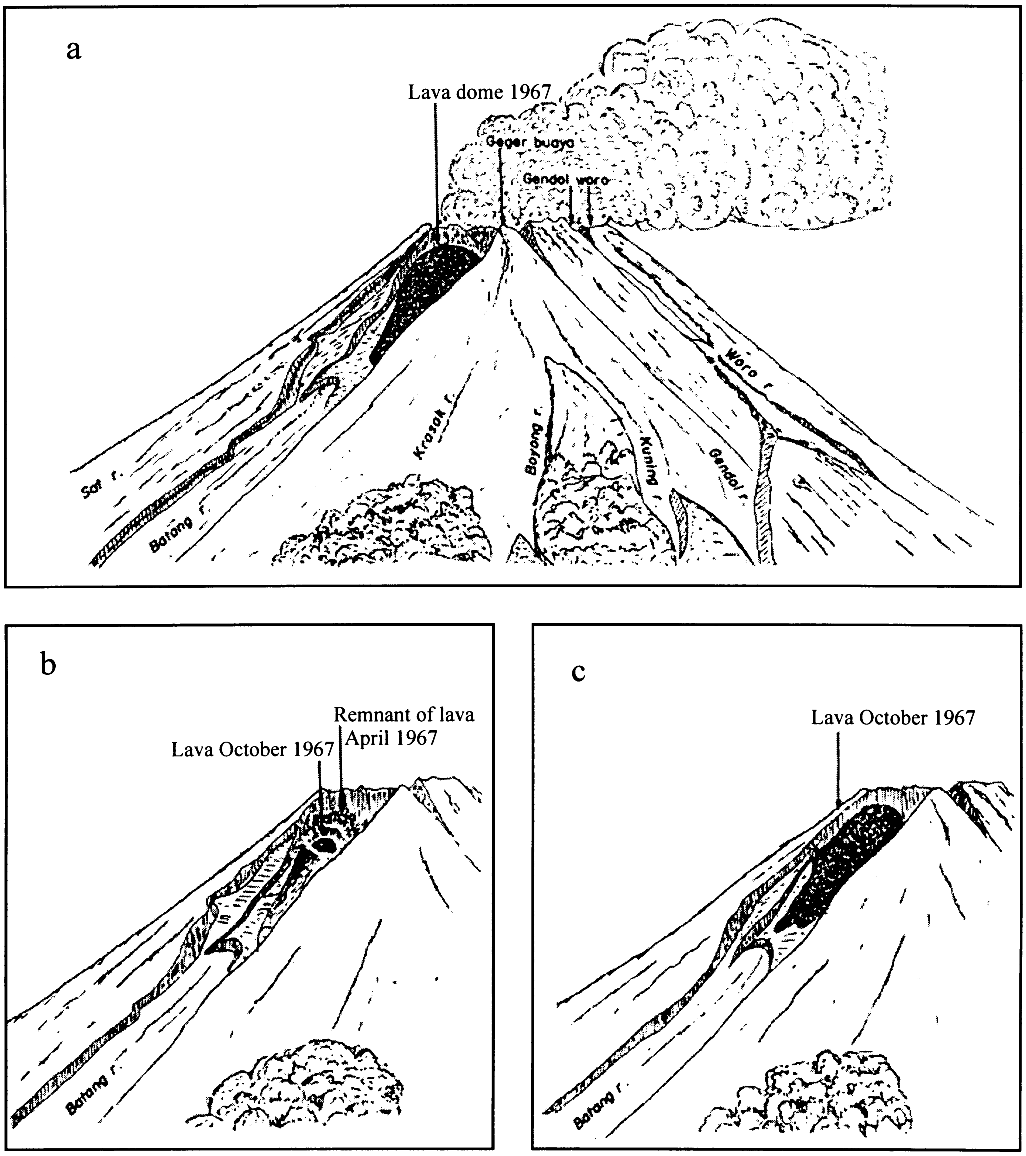


Fig. 38. Original sketches of Merapi as viewed from Plawangan post on the south in 1967–1968 (BVSI, no. 106). a. Lava dome in Batang breach on 25 September 1967. Sketch by I. Suryo. b. The dome collapsed on 7–9 October, generating 39 nuées ardentes in the main "eruptive" phase. Post-collapse view on 13 October, showing early appearance of October lava. Sketch by Sumidi. c. The October lava dome, as viewed on June 2, 1968. Sketch by S. Harto.

deformation through 1990 and 1991 (Young et al., 2000a–this volume). Electronic tiltmeters had been installed on the dome in 1990, and tripod-mounted COSPEC sulfur dioxide monitoring and digital seismic recording using IASPEI software was introduced in 1991.

1992–1993: Lava broke out on the northeast flank of the (mainly) 1984–1987 dome on 20 January 1992, accompanied by incandescent rockfalls and, after 31 January by dome-collapse nuées ardentes (Fig. 43). A minor explosion was reported with the peak of nuée activity on 2 February; the nuées travelled as far as

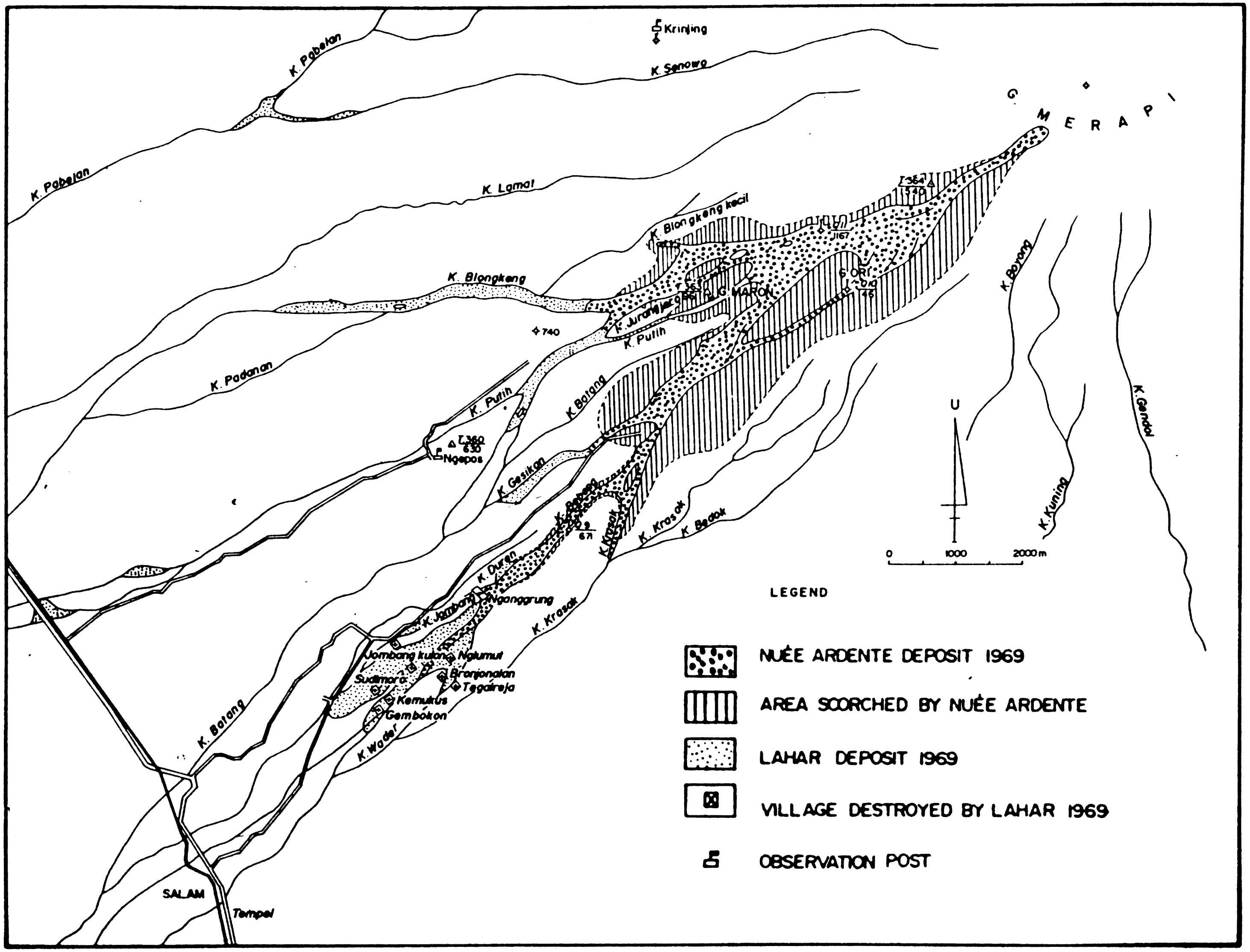


Fig. 39. Original sketch map of southwest flank of Merapi, showing area affected by nuées ardentes on 7–8 January 1969 (BVSI, no. 106). Legend: nuée ardente deposits of 1969, dotted pattern; scorched area affected by ash-cloud surges, lined pattern; lahar deposits of 1969, fine stipples; destroyed villages, crossed squares; observation posts at Krinjing, Ngepos, small rectangles with flags. Maximum runout of channeled block-and-ash flows was about 13 km in the Bebeng drainage.

4.5 km down the Sat valley. Nuée activity then declined but dome growth continued; the dome lava overlapped the northwest crater rim and caused incandescent rockfalls toward the Senowo. No evacuations were ordered. Hartmann A; VEI 2.

Additional brief nuée episodes occurred in April and August 1992, and in February 1993. Pulses of dome growth after late 1992 were detected by summit tiltmeters (Young et al., 2000b – this volume).

1994–1998: A resurgence of dome growth began in 1994, adding a new lobe directed to the southwest (Fig. 43). Since February 1994, rockfalls had produced a talus and rockfall deposit-buildup against the south runout-channel wall. As a result, some incandescent rockfalls were able to jump out of the channel and move down the south flank, towards the Boyong valley. This ominous development was insufficiently appreciated, because the south sector of Merapi had not been affected by hazardous events for a long time. On the morning of 22 November, with the 1994 dome volume about 2.6 million m^3, the dome collapsed over a 7-hour period in a series of nuées ardentes that travelled south–southwest, but also south, as far as 6.5 km (Fig. 44). In the Boyong

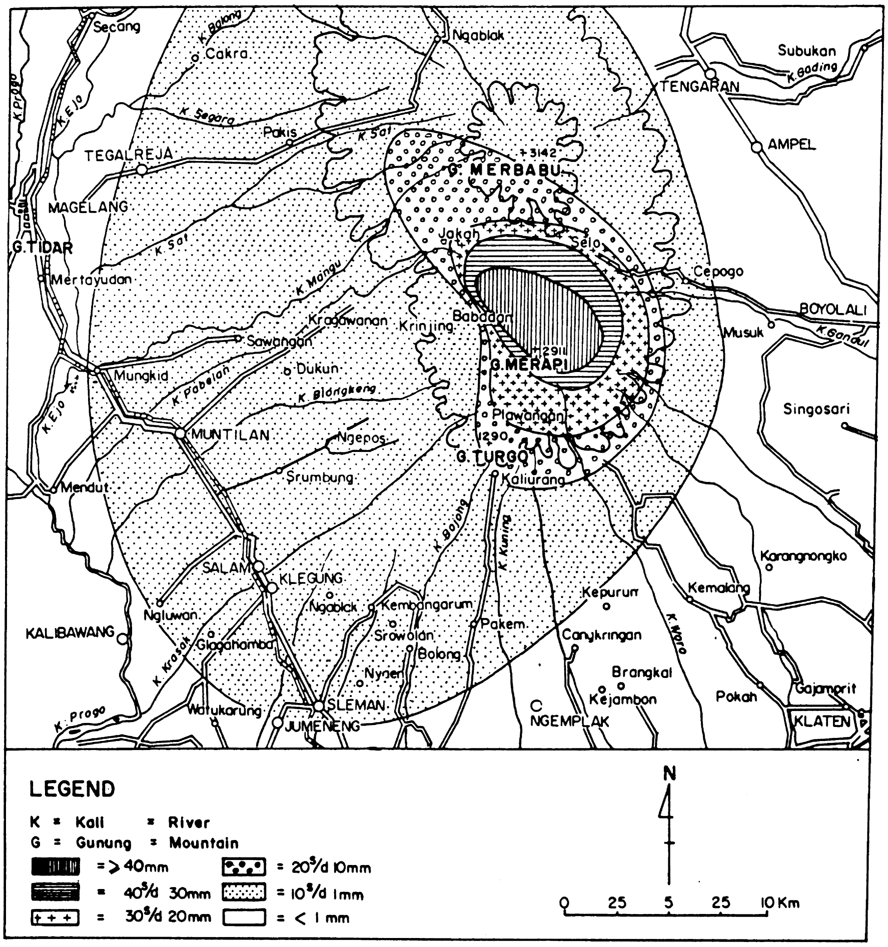
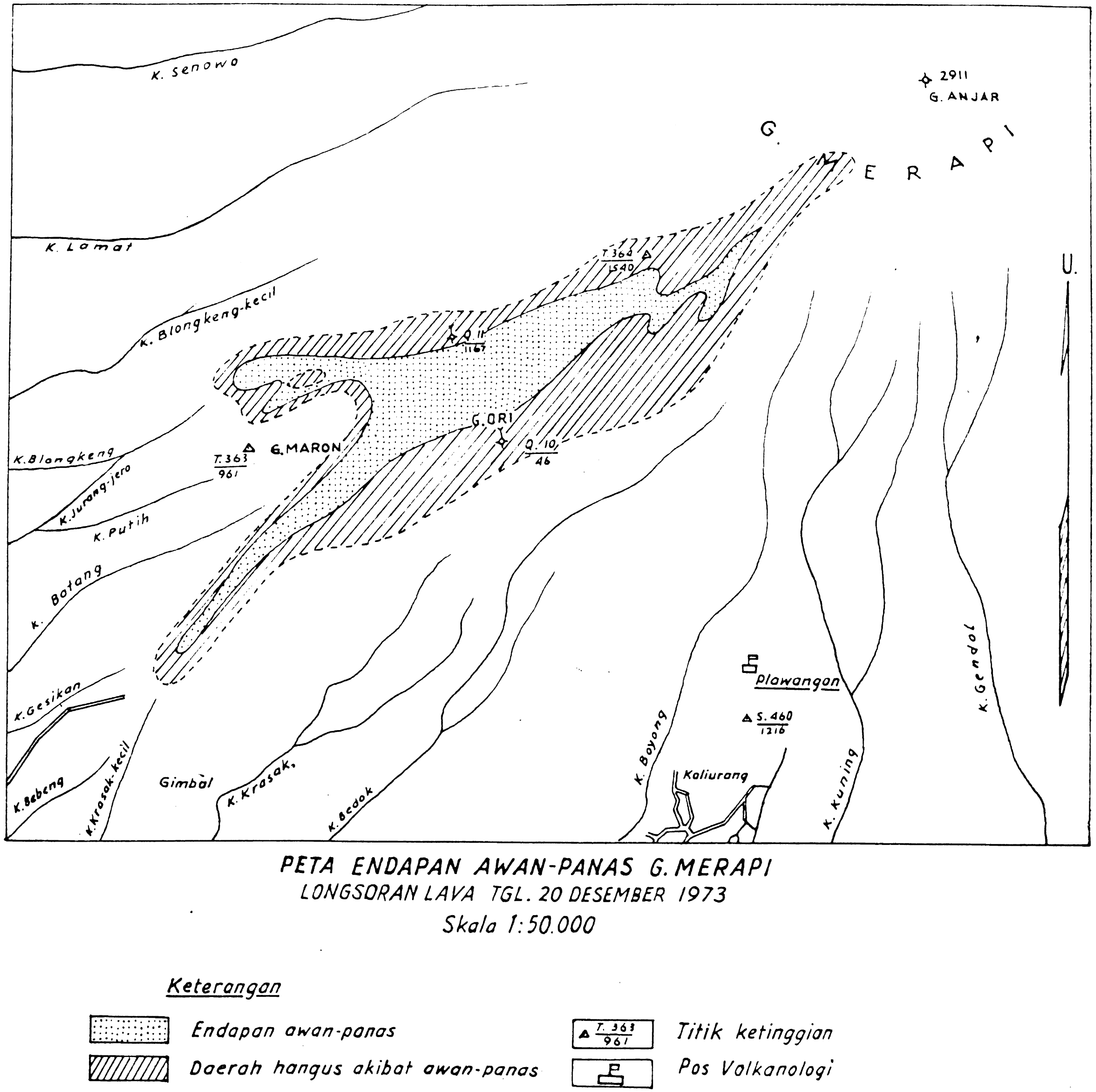


Fig. 40. Original map showing distribution of ashfall about Merapi during the eruption of 7–8 January 1969 (BVSI, no. 106). Shaded patterns indicate thickness of ash, from <1 mm (unshaded) to >40 mm (vertical line pattern). Regional reference points include towns of Sleman, Muntilan, Magelang, and Boyolali, and Merbabu Volcano. Wind blowing to the south resulted in several cm of ash on the barren slopes. This ash and the nuée ardente deposits were the source materials for devastating lahars.



K. Senowo
2911
G. ANJAR
G. MERAPI
U.
K. Lamat
T.364
1540
K. Blongkeng-kecil
Q.11
1167
G. ORI
Q.10
46
G. MARON
T.363
961
K. Blongkeng
K. Jurang-jero
K. Putih
K. Botang
K. Gesikan
K. Bebeng
K. Krasak-kecil
Gimbal
K. Krasak
K. Bedok
K. Boyong
Plawangan
S.460
1216
Kaliurang
K. Kuning
K. Gendol
PETA ENDAPAN AWAN-PANAS G. MERAPI
LONGSORAN LAVA TGL. 20 DESEMBER 1973
Skala 1:50.000
Keterangan
Endapan awan-panas
Daerah hangus akibat awan-panas
T.363
961
Titik ketinggian
Pos Volkanologi

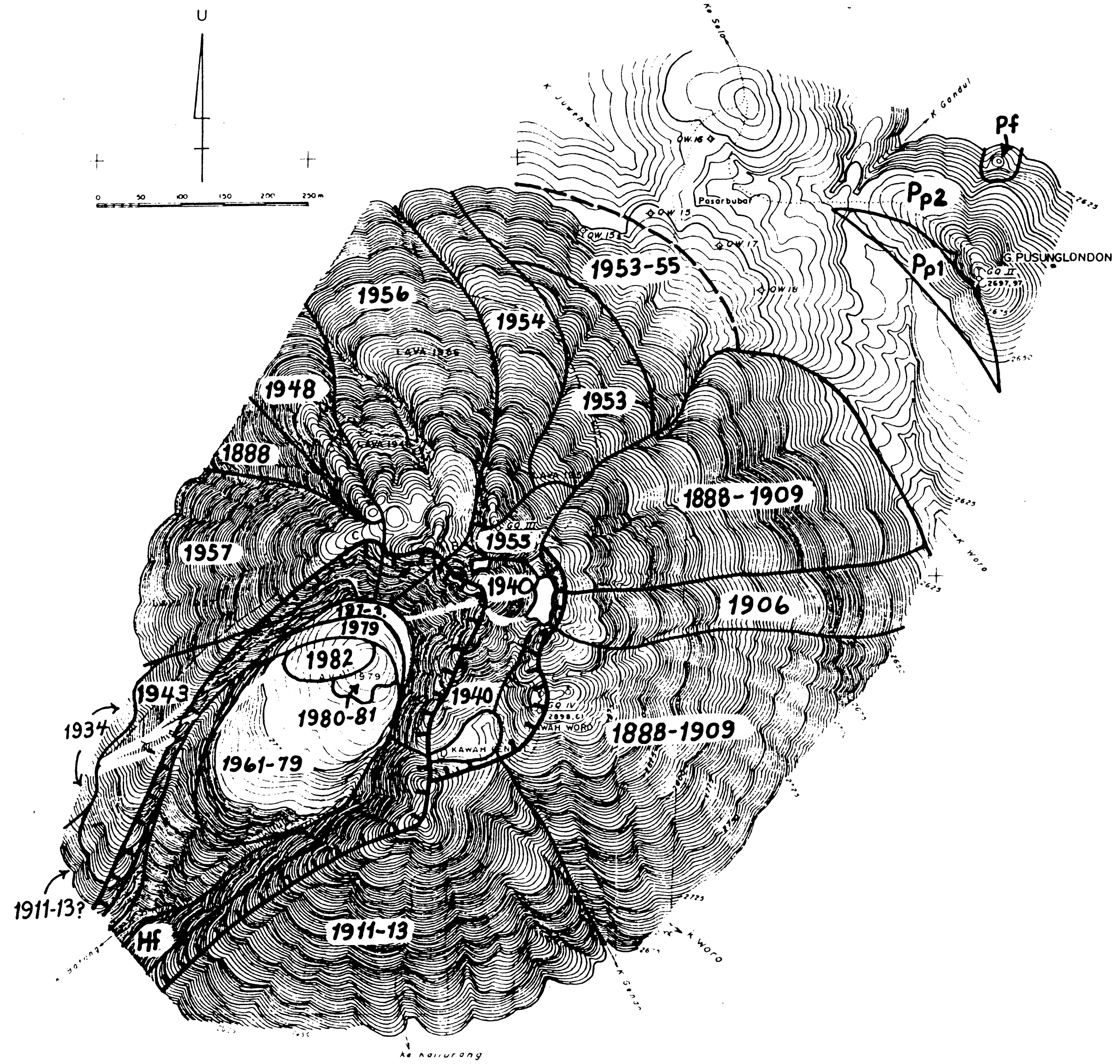


Fig. 42. Topography and interpreted ages of lava flows and dome lobes on Merapi summit (after unpublished map by R.T. Holcomb, A. Djumarma, and F. Suparban, 1982). Topographic survey of 1979. Provisional older units shown near G. Pusunglondon are *Pf*, a prehistoric lava flow; *Pp1* and *Pp2*, younger pyroclastic breccias separated by an unconformity; and *Hf* in the Batang breach, undifferentiated pre-1872 lava flows truncated to the northeast by the 1872 crater.

Fig. 41. Original sketch map of southwest flank of Merapi, showing area affected by dome-collapse nuées ardentes (*longsoran awan panas*) of 20 December 1973 (Siswowidjoyo and Harjowarsito, 1974). Map distinguishes nuée ardente deposits (stippled) and surrounding scorched zone (slanted line pattern). The summit of Merapi is denoted by G. Anjar. Flank reference points include G. Maron, G. Ori, and Plawangan post.

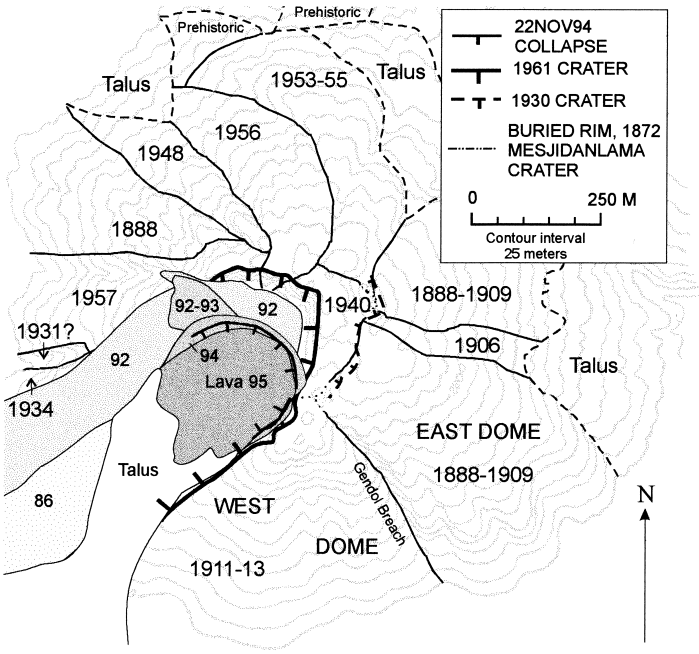


Fig. 43. Topography and interpreted ages of lava flows and dome lobes, with emphasis on activity in the late 1980s and 1990s. Topographic base map after Sajiman, MVO.

valley, near Turgo and Kaliurang, 64 were killed and dozens more seriously burned (Shelley and Voight, 1995). There were no recognized short-term precursors (Voight et al., 2000 – this volume). The deposits included block-and-ash channelled facies (ladu), widespread ash-cloud surge deposits, and fallout deposits of several types (Abdurachman et al., 2000 – this volume; Voight and Davis, 2000 – this volume). Lahars were mobilized subsequently by rainstorms (Lavigne et al., 2000a,b – this volume), and acoustic lahar detectors were installed by the USGS in February 1995. Over 6000 people were evacuated after the November disaster, and authorities decided to permanently resettle about 2700 persons from higher elevation villages.

In 1995, lava dome growth resumed from the vent of the collapsed lobe (Fig. 43). On 9 August 1996, a dome-collapse nuée moved 3.5 km to the upper reaches of the Boyong and Krasak drainages. Multiphase earthquakes and outward radial tilt increased in October, preceding a swarm of nuées. Important nuées ardentes, some with 6 km runout, also occurred in January 1997 and July 1998 (Fig. 44), and were preceded by strong tilt and seismic precursors that were recognised and aided decisions regarding evacuation by emergency management officials. The 1997 eruption included dome-collapse nuées ardentes on 14 January, and a vulcanian explosion on 17 January that produced a 4-km high plume and generated a fountain-collapse nuée ardente (Voight et al., 2000 – this volume). The 11 July eruption involved 36 nuées ardentes advancing southwest as far as 7 km, and another series of 25 nuées occurred on 19 July with runouts to 5.5 km. Hartmann B; VEI 2.

4. Discussion

4.1. Magma production in the last century

The lava production data since 1890 have been compiled by Siswowidjoyo et al. (1995, Table 1), and results are summarized in Fig. 45. The production rates of individual eruptive events have varied widely, but the cumulative volume has increased nearly linearly; this suggests that the lava production rate has been approximately constant for a century, at $0.1 \times 10^6\ m^3$ per month (Fig. 46). Periodic voluminous

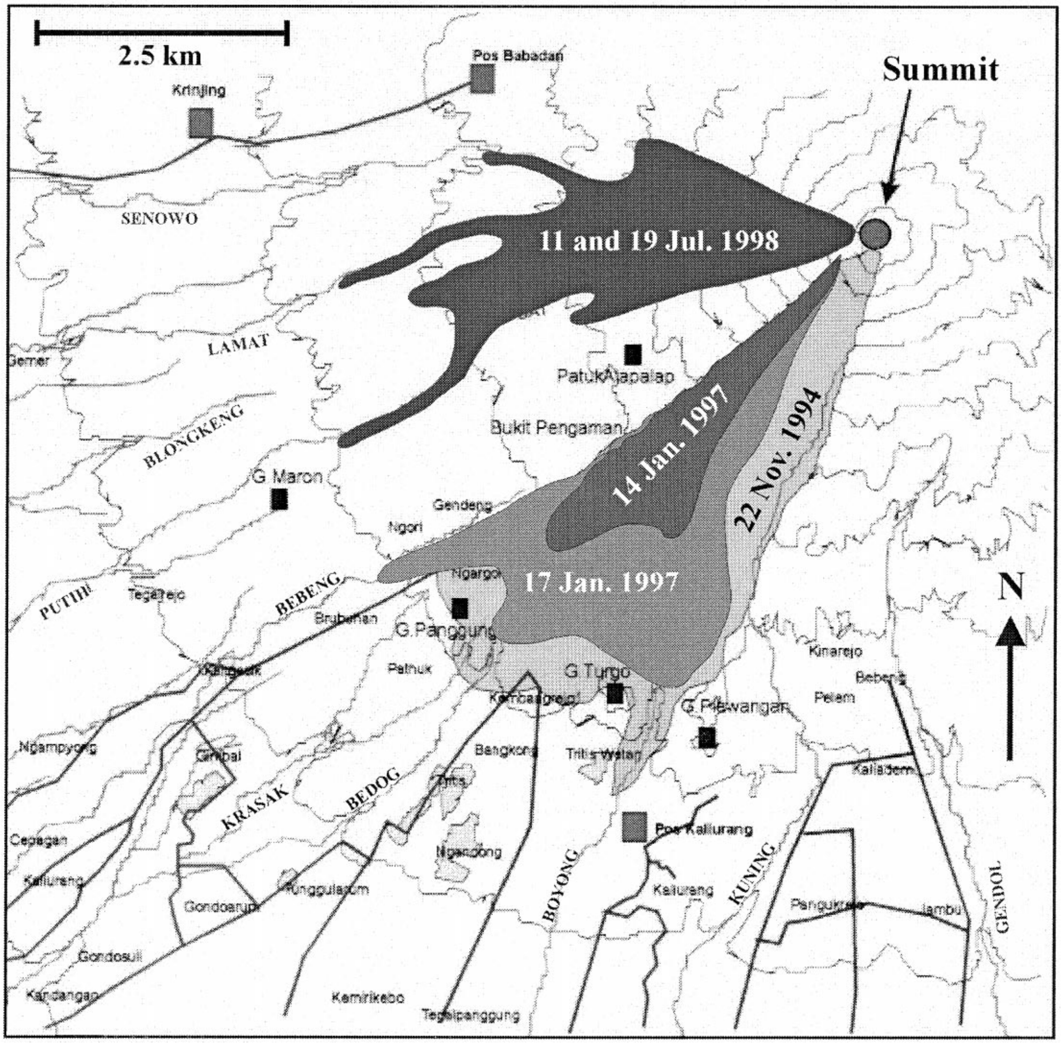


Fig. 44. Deposits of nuées ardentes on 22 November 1994, 14 and 17 January 1997, and 11 and 19 July 1998 (Voight et al., 2000 – this volume). Reference points include G. Maron, G. Panggun, G. Turgo, G. Plawangan, and observatory posts at Babadan and Kaliurang. Major drainages are named.

effusions ($>10^7$ m^3) reflect magma reservoir dynamics; such effusions have occurred five times this century, in 1907, 1930–1931, 1961, 1984–1989, and 1992-present. The first three of these eruptions involved short periods at high effusion rates. The data suggest that magma probably is being supplied more or less continuously, but is gradually stored in a reservoir which fills after about 20–30 years, before being discharged by a voluminous eruption. Such a time scale also seems to be broadly consistent with the occurrence of large events during the nineteenth century, although specific eruption rates for that period are not known.

Since 1871, the summit eruption sites have remained within a restricted region approximately delimited by the crater of 1846 (Figs. 47 and 48), indicating a relatively long-lived stability of the location of the conduit trunk system. The actual breakout points have shifted from time to time within that region, with conduit branches influenced by the local surface or shallow subsurface conditions of the vent or surface plug. The anomalous vent positions in

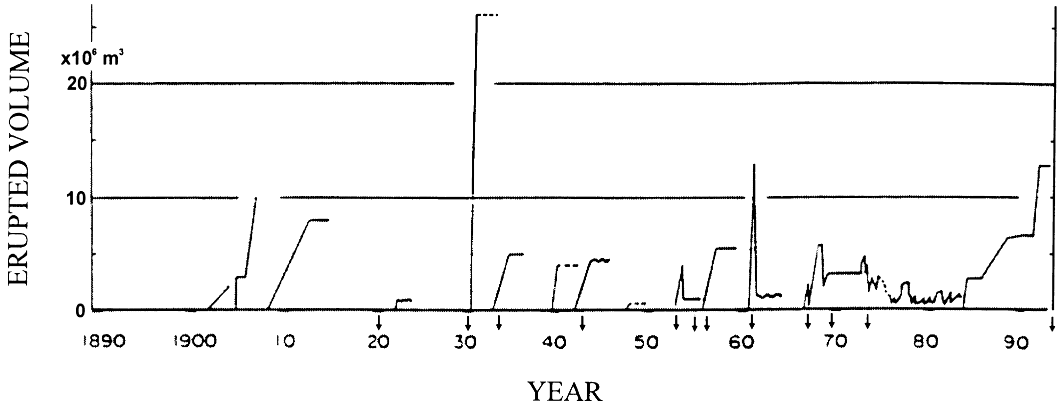


Fig. 45. Volume of erupted lava at Merapi and its major eruptions between 1890 and 1992 (Siswowidjoyo et al., 1995). Upward-sloping lines against time axis indicate lava extrusions, and downward-sloping lines collapses. Horizontal lines after effusions show the state of these lavas as of 1993: solid lines are lavas that still "existed" in 1993; dashed lines are "partly-existing" lavas; wavy lines, erupted lavas that no longer exist. Down-pointing arrows indicate times of important nuées ardentes.

1922 and 1930 probably reflect near-surface obstruction of the conduit by the large East Dome and West Dome complex (Fig. 17).

4.2. Volatile production

Data on gas emissions and volatiles dissolved in lava are discussed by LeGuern et al., 1982, Sayudi and Sulistiyo (1994), Sri Sumarti and Suryono (1994), among others, and are reviewed by Allard et al. (1995). Chemical and isotopic analyses of the high-temperature (600–900°C) gases emitted from the Woro-Gendol fumarolic fields and the lava dome itself indicate a common magmatic

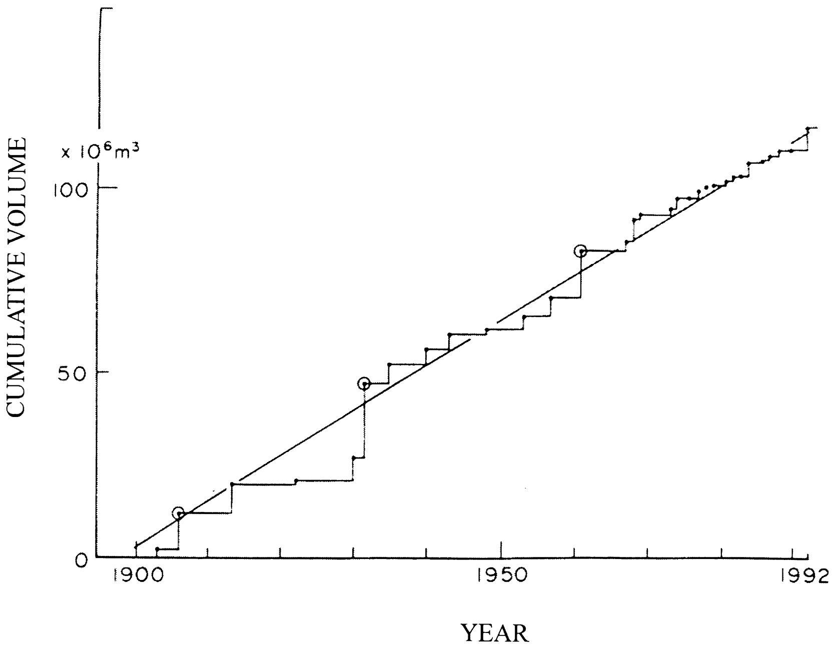


Fig. 46. Cumulative volume of lavas from Merapi volcano since 1900 (Siswowidjoyo et al., 1995). Circles denote accumulation of lava volumes exceeding 10 million m^3 in a single eruption episode.

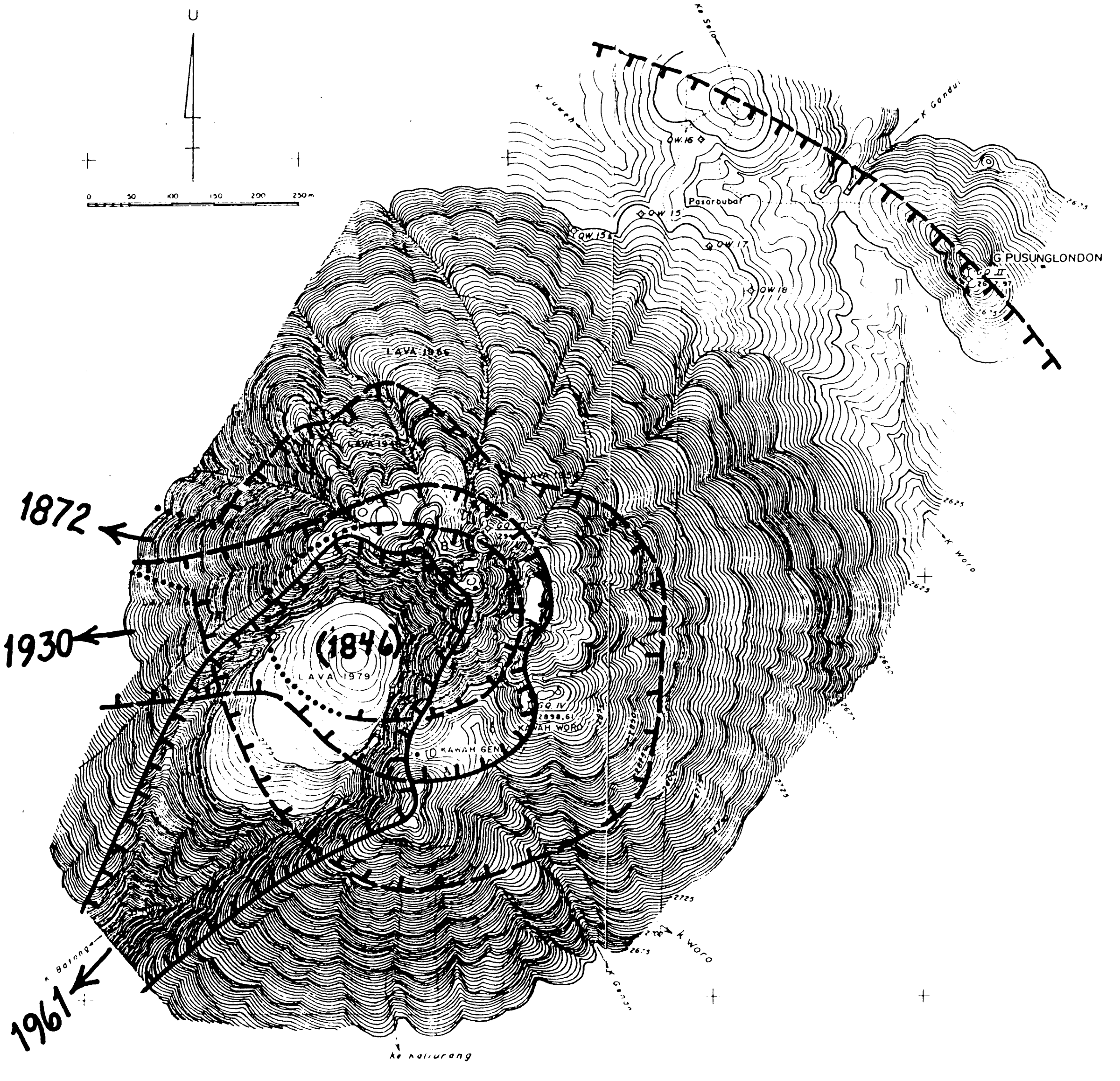


Fig. 47. Topography and boundaries of former craters of 1846, 1872, 1930, and then-active 1961 crater. Ancient collapse boundary (undated) shown through G. Pusunglondon (Unpublished map by R.T. Holcomb, USGS, 1982).

fluid feeding all emissions. This magmatic fluid, analyzed on different dates, has a representative mean composition (% vol) of H_2O (83.0), CO_2 (12.7), H_2 (1.3), SO_2 (1.0), H_2S (1.0), HCl (0.9), HF (0.025), CO (0.024), N_2 (0.01), COS (3.5×10^{-3}), CH_4 (1.7×10^{-3}), ^3He (2×10^{-4}). Isotopic data indicate a true magmatic origin of most species, with the contribution of a subducted crustal component in the case of water, sulfur, and nitrogen. Carbon and helium derive principally from the mantle, with minor crustal additions being allowed by higher-than-MORB $CO_2/^3He$ ratio, and carbonate xenoliths in Merapi lavas.

Probably most of the gas emitted at Merapi occurs

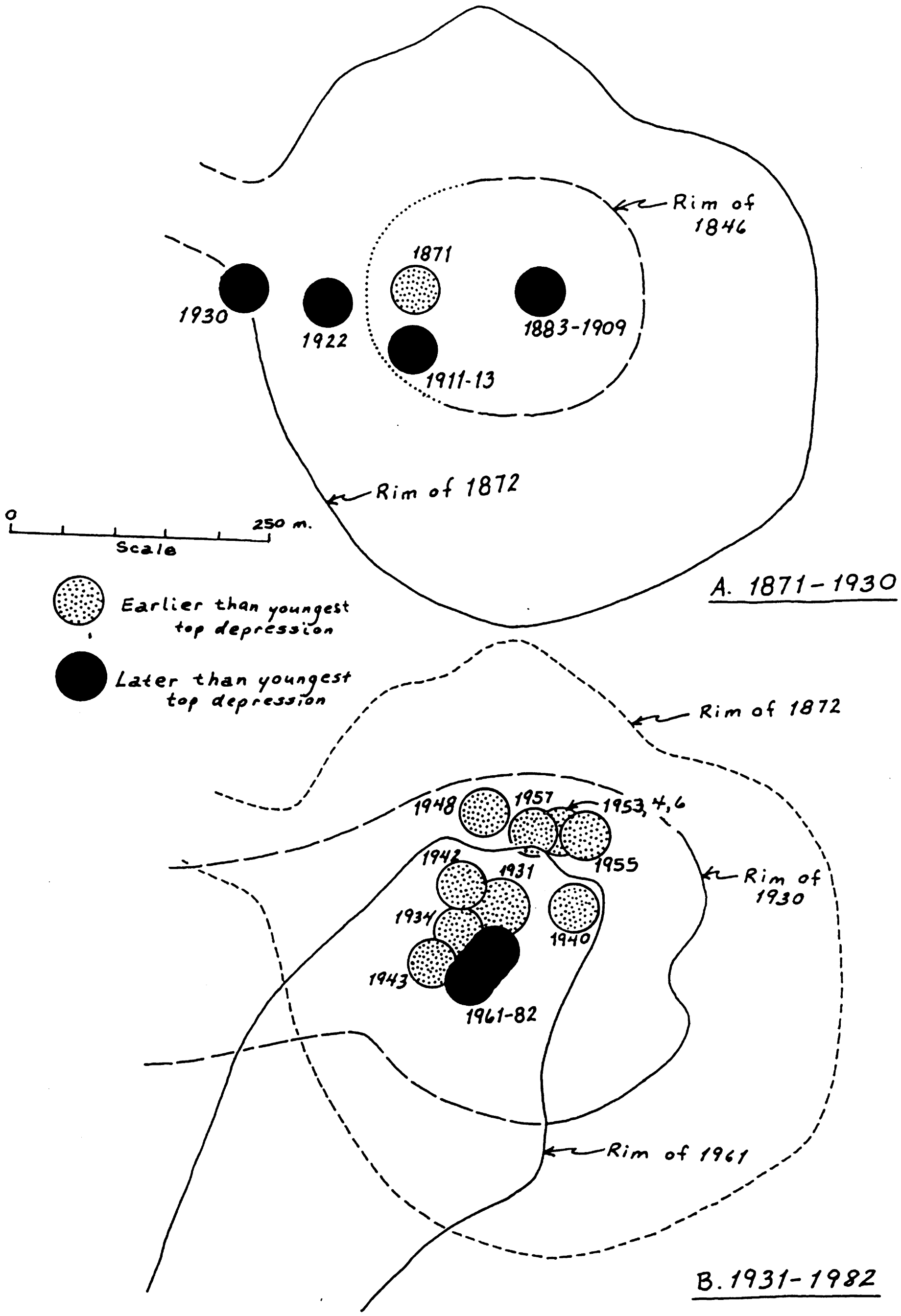


Fig. 48. Original sketch map of summit area of Merapi, indicating eruption sites for two periods, (a) 1871–1930, and (b) 1931–1882. Reference positions are indicated for crater rims of 1846, 1872, 1930, 1961 (Unpublished map by R.T. Holcomb, USGS, 1982).

during quiescent lava extrusion, because paroxysmal phases are brief and episodic events. Combining the mean composition of the high-temperature gases with correlation-spectrometer measurements of the SO_2 plume flux allows an estimate of the time-averaged output of each gas compound (tonnes per day): H_2O (4400), CO_2 (1700), SO_2 (200), H_2S (100), HCl (90), HF (1.5), H_2 (1.6×10^{-3}), and ^3He (1.1 × 10-8). The total gas output (6500 tonnes per day or 2.4×10^6 tonnes per year) characterizes Merapi as a medium emittor among persistently degassing arc volcanoes, producing as much ^3He as a 60-km-long section of the mid-ocean ridge system. Some abrupt variations of fumarole gas ratios have been observed before or during recent eruptive events (Sayudi and Sulistiyo, 1994).

Microprobe analysis of volatiles trapped in melt inclusions of olivine and pyroxene phenocrysts in Merapi andesite indicate an initial sulfur content of >950 ppm by weight in the magma. Normalizing the sulfur gas output to the degassed fraction of S then suggests a magma-degassing rate of 1.3×10^5 m^3 per day (~0.05 km^3 per year). A similar rate is obtained using the activity of Po-210, a long-lived radioactive daughter of radon, in the gases and the lava (M.F. Le Cloarec, unpublished data). Such a degassing rate is 40 times greater than the lava extrusion rate over the past century (Fig. 46). "Excess" sulfur emission rates have been documented during lava dome growth at Redoubt, Unzen, and Soufriere Hills volcanoes, as well as for large eruptions at El Chichon and Pinatubo (Gerlach et al., 1994; Kress, 1997; Keppler, 1999).

Allard et al. (1995) conclude that Merapi produces as much gas as lava by mass, and suggest that a key factor controlling eruptive activity is the ratio between the rates of gas supply and gas release. Both rates are likely to equilibrate on the long-term, but may diverge on shorter time scales, depending on the aperture of the conduits. A progressive blockage of the conduits by a stable lava dome can reduce gas escape and cause a build-up of gas pressure in the magma, increasing its potential for an explosive eruption. Considering simultaneously the gas output and the magma extrusion rate could help to discriminate whether a progressive decrease of gas output is due to lower gas supply from depth (little hazard) or a progressive reduction of gas permeability (increasing hazard).

4.3. Patterns of eruptions

The eruptive episodes since 1768 are summarized in Table 2 with the notation indicating periods of activity, eruption style, types of nuée ardente, Hartmann classification, and VEI. In this paper, in many cases we have accepted classifications designated by earlier workers, but have altered rankings in some cases. Some values listed in this paper are provisional or uncertain, as indicated by a question-mark. If, for instance, the beginning of an eruptive episode is unclear (as is not uncommon), it may also be unclear whether a given explosion should be considered a fore-phase event, or as a main-phase event during ongoing activity. The question is illustrated by the 1939–1941 activity, which began with explosion plumes that rose >3 km above the summit, but was ranked as class A by Van Bemmelen (1949). Other problems are discussed by Siswowidjoyo (1984); Ratdomopurbo and Poupinet (2000 – this volume).

Table 2 shows at a glance the relative "size" of events occuring in any period, and enables useful comparisons to be made between time periods. A clear pattern is the greater frequency of explosions and fountain-collapse nuées ardentes that occurred in the 1800s, compared to the 1900s. Fountain-collapse nuées ardentes appear to be dominant to the 1870s; apparently the pattern then changed to one of periodic viscous effusions punctuated by episodes of generation of dome-collapse nuées ardentes. This has been the dominant pattern of the twentieth century, and only rarely, as in the abnormal event of 1930, did dome-collapse pyroclastic currents reach beyond 10 km from the summit.

Likewise, the original Hartmann classifications show a number of C and D events to the 1870s, but mainly only A and B thereafter. Some of the C ratings seem questionable to us and we have reduced them. Nonetheless, only one class C eruption occurred in the twentieth century, in 1934, also in association with fountain-collapse nuées ardentes. Obviously, there is a linkage between Hartmann class and nuée type. Because class C and D events produce vertical eruption columns, associated fountain-collapse nuées ardentes can be expected; if the erupted volume is large enough, the nuées can be broadly distributed about the volcano, rather than restricted to narrow sectors as in conventional dome-collapse. For example, on 7 May 1961, an eruption plume rose 3 km over the Merapi summit, and generated nuées ardentes mostly to the west and southwest between the Senowo and Batang; also, nuées passed through crater rim breaches to the Woro and Gendol drainages to the south–southeast. However, this event is ranked as class B, because of the extensive fore-phase activity. Most notable in the respect of broadly distributed eruption products was the explosive eruption of 1872, a class D event.

The assignment of nuée type is commonly not a simple task from the evidence available, and some interpretations reported in the literature may not be correct. Reports of "explosions" may or may not be reliable; some reports have been given on the basis of sounds, but loud noises can be generated from dome collapse as well as by true explosions. Explosive activity is not a prerequisite to generate a nuée ardente. An ash plume over the summit can be produced by a vertical explosion, but a vertical plume can also result from strong convection of hot dust produced with early disintegration of a dome-collapse nuée ardente, or of hot gassy ash spalling from the scar of a dome "rockslide." Further, authentic but minor explosions can create a convecting plume rising many km above the dome, at the same time that the main parts of the dome are collapsing by gravity. In these cases the nuées are of the dome-collapse type, as eruption fountain-collapse has not produced them, but observers might have been inclined to define the events as due to fountain-collapse on the visual basis of a high plume. Further complications are introduced by hybrid events, e.g. nuées that start by dome-collapse but trigger explosions, and explosions that trigger dome collapse (C. Newhall, written communication).

Both for Hartmann and VEI rankings, the validity of values is highly dependent on the abundance and quality of observations and measurements. The distinction between nineteenth and twentieth century activity is less clear from the perspective of VEI rankings. In Smithsonian Institution compilations, VEI 3 events are scattered throughout the entire time period evaluated, but it is likely that these estimated rankings are not always accurate, as many were assigned before detailed summaries were available (C. Newhall, written communication). Nuées ardentes eruptions are especially hard to rank. In terms of volume released, dome-collapse events occur generally in the range of 10^6 m^3 to, rarely, 10^7 m^3. This indicates that most events should be in the VEI 2 class, with the largest events (as in 1961) near the boundary of VEI 2 and 3. In our summary, some rankings may be overvalued, although we have reduced the grade of many. We suggest VEI ≥ 3 eruptions probably occurred 4 times in the 1800s: in 1822, (possibly 1832), 1846, 1849, and 1872, compared to only twice in the 1900s, in 1930 and 1961. In any case, only the VEI 4 eruption of 1872 (Hartmann D) stands out from the VEI distributions, with the 1822 eruption also possibly of this grade.

One must be careful about correlating the historical data with the mid- to late-Holocene record (C. Newhall, written communication). This record (Andreastuti et al., 2000 – this volume) suggests that the apparent recurrence period for VEI 4 events, about the scale of 1982 Galunggung, is about 100–200 years, and that for VEI 5 is about 1000 years. These recurrence periods may be overestimates, because probably not all tephras or nuée deposits for these size events have been recognized.

4.4. Eruption monitoring and eruption precursors

No volcano in Indonesia has been better monitored than Merapi, but it must be emphasized that systematic monitoring was unavailable for the early events, including the largest and most important eruptions. Any precursors for these early events are recognized only through non-systematic visual observations and felt earthquakes. Later in the nineteenth century, geodetic measurements were used to characterize summit geometry, and elevation changes were occasionally noted and interpreted. Temperatures of certain fumaroles have been recorded systematically at Merapi since 1924, occasionally indicating changes in relation to eruptive activity in the 1930s and 1940s (Neumann van Padang, 1933, 1960; Van Bemmelen, 1949). Early opinion had been that a temperature rise would provide a simple, clear and useful indication of impending eruption. Unfortunately, in retrospect this supposition has not proven to be true (Neumann van Padang, 1963, 1983).

Detailed studies of sublimate and gas geochemistry of fumaroles were begun by French scientists in the

1970s (Allard and Tazieff, 1979; LeGuern and Bernard, 1982; LeGuern et al., 1982), and have continued for three decades (Symonds et al., 1987; Allard et al., 1995). Sharp variations of H_2O/gas, C/S and Cl/S ratios were observed before and during several recent eruptive events (Sayudi and Sulistiyo, 1994).

The first seismograph was introduced in 1924, marking the first time that non-felt seismicity had been recognised as an important precursor of Merapi activity. With the importance of seismic monitoring evident, many improvements were made: a mechanical (Weichert) seismograph, magnification 200, was added in 1957 and still operates; electromagnetic instruments were added in 1961–1965 and then removed in 1968 due to high costs in relation to available funds; a brief study by Shimozuru et al. (1969) in 1968 resulted in an early classification system to guide the interpretation of seismic source processes (Siswowidjoyo, 1984). The first seismic network, enabling for the first time precise foci locations, was installed in 1982 by USGS-VSI collaborating scientists. Subsequent additional improvements made to the network include digital recording and processing software from French scientists in 1991, real-time seismic amplitude monitoring (RSAM) and seismic spectral amplitude monitoring (SSAM) systems from Penn State University scientists (with USGS collaboration) in the 1990s, and further upgrading of data acquisition and analysis hardware and software by the USGS/USAID Volcano Crisis Assistance Team (VCAT) in 1995. Meanwhile, independent studies of seismicity were initiated by Gadjah Mada University (Yogya) by Prof. R. Mugiono and R. Schick and other collaborating German scientists since the mid-1980s, with digital equipment, and since 1994, with broadband instrumentation (Fadeli, 1992; Brodscholl et al., 2000 – this volume). German scientists have also developed collaborations with VSI. A summit broadband experimental deployment at the Merapi summit was carried out in 1998 by collaborating Penn State and VSI scientists (Hidayat et al., 2000 – this volume).

As regards deformation monitoring, flank electronic distance measurements (EDM) were attempted briefly in the early 1980s (Siswowidjoyo et al., 1985), then discontinued; EDM was reintroduced in 1988, utilizing both flank and summit networks since that time (Young et al., 2000 – this volume). GPS was used over the over last few years, along with gravity measurements, using many benchmarks of the EDM summit network (Jousset et al., 2000 – this volume). Early attempts at tilt monitoring started in the 1930s but modern electronic tilt instrumentation began only in 1990, and has operated continuously since 1992 (Voight et al., 2000 – this volume; Beauducel and Cornet, 1999; Young et al., 2000b – this volume). Other types of instrumentation, much of it experimental, also have been tested at Merapi. Magnetic monitoring has been developed by French scientists (Zlotnicki and Bof, 1997). Sound monitoring was attempted in 1943, and infrasonic monitoring has been developed in the 1990s by Japanese scientists in collaboration with VSI.

The above brief review indicates that instrumental monitoring has provided insights from the 1920s onward; some significant steps were taken in the 1960s and 1970s, but modern seismic analysis with precise earthquake source locations began only in 1982. Modern deformation work really produced results only since the 1990s. In short, only very limited information on precursory processes and detection is available for most of the previous events at Merapi. Thus, “up to 1883, one can conclude that felt earthquakes would often precede eruptions, but from the old sources one cannot distinguish between volcanic and tectonic earthquakes” (Hartmann, 1935a). Probably in most cases of felt seismicity near the volcano, the source is most likely to have been volcano seismicity. However, for some cases there is indeed a suggestion of an association of eruptive activity with large subduction-related tectonic earthquakes. Most instrumental precursory seismicity relates to volcanic unrest, with activity since about 1967 best (but still only partly) understood (Siswowidjoyo, 1984; Siswowidjoyo et al., 1985; Ratdomopurbo and Poupinet, 2000 – this volume). Precursory deformation and seismicity were strong for two years prior to the undramatic (but voluminous) 1992 eruption. However, the significant November 1994 collapse episode, that caused many deaths, apparently resulted from gravitational instability associated with nearly steady-state effusion onto a slope; no immediate seismic or deformation precursors were detected. On the other hand, tilt and seismic precursors were recognized before important nuées in 1997 and 1998, and aided mitigation measures.

Thus, overall there has been complexity, with little reliable diagnostic precursory information. The database is limited and not very systematic, and no data are available to date for the largest class of eruption. Although recent progress is encouraging in many respects, the database does not provide sufficient information on precursory patterns to enable necessarily reliable forecasts for potential future activity.

4.5. Impact of historical eruptions on hazard evaluation

Although the size of Merapi events have appeared to decrease in the twentieth century, those concerned with hazard management should be exercise caution. There is a tendency to let recent small events dictate hazard zonation, whereas there is no guarantee that the recent pattern of small to modest-sized events will be the norm in the future. Thus, the present zonation map has its roots in twentieth century events, most notably that of 1930 (Neumann van Padang, 1933; 1960; BNEIVS, no. 95–98; BVSI, no. 104). Yet, might the pattern of the 1800s return? The question can be evaluated by examining Merapi's earlier eruptive history, using volcanic stratigraphy and age dating. This has been done by Newhall et al. (2000 – this volume), who conclude that many eruptions from the 7th through the nineteenth centuries have been relatively violent—much larger than any in the twentieth century—and have swept broad sectors of Merapi with nuées ardentes, in some cases, >20 km from the summit. Similar results extending back to the mid-Holocene are documented by Andreastuti et al. (2000 – this volume). Newhall et al. conclude that these larger eruptions have occurred on average once per century. Thus, the nineteenth century *is* approximately representative of the long-term eruptive record of Merapi, and larger explosive eruptions *should* be expected in the future. Volcanologists and hazard managers should fully appreciate that Merapi not only produces Merapi-type nuées ardentes from dome collapse, but also larger, potentially farther-reaching fountain-collapse nuées ardentes from infrequent, but relatively large, explosive eruptions, and that these eruptions can affect sectors that may not be obvious from summit topographic factors alone.

The potential for larger, more destructive eruptions was recognized by the Dutch volcanologists earlier in this century, who were more familiar with events of the 1800s. Thus Kemmerling (1921) noted, "Three times in the nineteenth century the lava dome was destroyed, in 1822, 1849, and 1872, that is with an interval of 27 and 23 years. The present condition (i.e. 1920) has lasted since 1883, that is to say, 37 years; if we, observing the antecedents, venture a forecast, then based on this we may expect a total destruction in the near future." To a certain extent, the eruption of 1930 may have "satisfied" this forecast, although the style of event was complex and not really comparable to those noted above; also, as noted above, the frequency of "larger" magma production events has been maintained. The simple fact remains that explosive destruction of the Merapi summit in the future should not be excluded, and indeed may be expected, perhaps in the 21st century.

Further implications concern the hazard-zone boundaries themselves, and their influence on land management. The "so-called forbidden zone" [the same phrase was used by Van Bemmelen in 1941 (BNEIVS, no. 95–98)] now has at least 80,000 people living inside its boundaries, and hundreds of thousands more just outside it (F. Lavigne, written communication). Communities and land-development projects are being built on youthful pyroclastic deposits containing charcoal that indicates that high-temperature ash currents had swept, not so long ago, the same landscape, and far beyond the current danger zone boundaries. Further, the forbidden zone mainly involves the areas to the west and southwest of the Merapi summit, where most eruptions of recent memory have occurred, and only small sectors of the zone have been evacuated in recent eruptions (Newhall et al., 2000 – this volume). The zonation and recent mitigation actions are not conservative, given the possibility of larger, explosively produced nuées ardentes that could impact nearly all sides of the volcano.

Would an eruption on the scale of 1822 or 1872 be accompanied by clear precursors, distinctive from those for less-severe eruptions? As discussed above, the historical record is not clear on this point, for scientific monitoring programs did not exist when these eruptions occurred over 100 years ago. However, the narratives suggest that the precursors, if any, may have been relatively modest, or at least, indistinct from; say, those of the vulcanian eruption of

January 1997 (Voight et al., 2000 – this volume). Although modern monitoring would surely detect seismic, deformation and other geophysical or geochemical signatures, it is not at all certain that the onset of a large, explosive eruption would be recognized and interpreted correctly in advance, *with the confidence and conviction needed to convince officials to carry out massive evacuations*.

5. Conclusions

A history of over two centuries of eruptive activity at Merapi has been reconstructed from various sources, with the information organized in chronological order so that it may serve as a concise, reasonably comprehensive information source and a guide to the literature.

A major difference in eruption style exists between the activity of the twentieth century and that of the previous centuries, although the frequency of larger events seems about the same. Twentieth century activity mainly comprises effusive growth of viscous lava domes and lava tongues, oversteepened parts of which gravitationally collapse to produce the nuées ardentes style commonly defined as “Merapi-type”. In the 1800s, however, larger explosive eruptions occurred, and the associated fountain-collapse nuées ardentes were larger and travelled farther than any produced in the twentieth century. These events, too, may be regarded as typical eruptions for Merapi.

Although the eruptive style of Merapi seems to have changed, the considerable hazards associated with the previous, more dangerous eruption style must not be ignored. The nineteenth century activity is consistent with the pattern of one relatively large event every century or so, based on the long-term eruptive record deduced from stratigraphic, mapping, and age-dating studies (Newhall et al., 2000 – this volume; Andreastuti et al., 2000 – this volume). Relatively large events have occurred many times in the past and will certainly happen again. Activity in the twentieth Century has been anomalously mild. The occurrence of such a large event, with only modest (or inadequately appreciated) precursors, could lead to a disaster unprecedented in Merapi’s history—given the large and increasing population living on the volcano flanks. We conclude that a recurrence of the kind of large explosive events typical of the 1800s is likely in the future, and that current hazard evaluations should not play down the possibility of these larger eruptive events, despite the dominance of smaller events in the twentieth century record.

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