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Deformation and seismic precursors to dome-collapse and fountain-collapse nuées ardentes at Merapi Volcano, Java, Indonesia, 1994–1998

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Abstract

Following the eruption of January 1992, episodes of lava dome growth accompanied by generation of dome-collapse nuées ardentes occurred in 1994–1998. In addition, nuées ardentes were generated by fountain-collapse in January 1997, and the 1998 events also suggest an explosive component. Significant tilt and seismic precursors on varying time scales preceded these events. Deformation about the summit has been detected by electronic tiltmeters since November 1992, with inflation corresponding generally to lava dome growth, and deflation (or decreased inflation) corresponding to loss of dome mass. Strong short-term (days to weeks) accelerations in tilt rate and seismicity occurred prior to the major nuées ardentes episodes, apart from those of 22 November 1994 which were preceded by steadily increasing tilt for over 200 days but lacked short-term precursors. Because of the combination of populated hazardous areas and the lack of an issued warning, about 100 casualties occurred in 1994. In contrast, the strong precursors in 1997 and 1998 provided advance warning to observatory scientists, enabled the stepped raising of alert levels, and aided hazard management. As a result of these factors, but also the fortunate fact that the large nuées ardentes did not quite descend into populated areas, no casualties occurred. The nuée ardente episode of 1994 is interpreted as purely due to gravitational collapse, whereas those of 1997 and 1998 were influenced by gas-pressurization of the lava dome.

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

1. Introduction

Merapi in central Java is one of the most active and dangerous stratovolcanoes on earth, owing to its andesitic lava dome and edifice instability, its long history of violent explosive activity, and the presence of a large and vulnerable population on its flanks. The recent activity of Merapi has been characterized by repeated episodes of dome growth and collapse, interspersed on occasion by vulcanian explosions (Voight et al., 2000 – this volume; Newhall et al., 2000 – this volume). The most recent phase of activity began in

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January 1992 (Ratdomopurbo and Poupinet, 2000 – this volume), with lava dome growth relatively continuous but episodic in rate of effusion, and occasionally punctuated by generation of nuées ardentes (SEAN, v.17(2),18(1)). Notable nuées ardentes occurred in 1994, 1996/1997, and 1998.

Monitoring of Merapi using various techniques is discussed in a number of papers in this volume (Ratdomopurbo and Poupinet, 2000 – this volume; Young et al., 2000 – this volume; Jousset et al., 2000 – this volume; Zlotnicki et al., 2000 – this volume). In this paper we focus on real-time deformation and seismic monitoring and its relation to the most significant of the nuée ardente episodes occurring between November 1994 and July 1998. We explore the extent to which the monitored data provide recognizable precursors to the nuées ardentes, and the extent to which this data was useful, or not useful, to hazard mitigation. We examine the data in relation to the two types of nuée ardente activity that occurred, by dome-collapse and by fountain-collapse, partly to ascertain whether the different event types can be anticipated by monitoring.

2. Monitoring methods

The Merapi Volcano Observatory (MVO) seismic network is fully discussed by Ratdomopurbo and Poupinet (2000 – this volume), and the general background on deformation monitoring is discussed by Young et al. (2000 – this volume). Electronic tilt near the summit has been monitored since 1990, and more or less continuously since November 1992 by collaborating Penn State, USGS and MVO scientists (Young et al., 1994). Japanese scientists have also installed instruments. Generally the periods of inflation corresponded to lava dome growth; the periods of deflation, or decreases in inflation, followed occurrences of pyroclastic flows. Recently, additional tiltmeters have been installed and operated by French universities (Beauducel and Cornet, 2000 – this volume), and German universities (Rebscher et al., 1997), in cooperation with MVO; these studies are outside the scope of this paper. Complimentary deformation studies have been conducted, such as the repetitive EDM measurements (Young et al., 2000 – this volume) and the repetitive GPS measurements (Jousset et al., 2000 – this volume; Beauducel and Cornet, 1999). In general such measurements are repeated over intervals of many months, although more frequent measurements can be made during times of crisis, particularly using EDM to fixed reflectors. All studies indicate that substantial deformation and volcanic seismicity has occurred during the recent activity at Merapi, and that the observations could be used to understand the geometry and dynamics of the magmatic systems within the volcano, as well as to recognize precursors for future eruptions.

3. Instrumentation and data

3.1. Tiltmetry

We discuss data for several tiltmeters installed near the summit, and others at mid-flank or lower flank locations. These instruments were installed and operated in collaborative projects involving Penn State University, the USGS and MVO. Generally (especially at the summit) tilt stations consist of paired high- and low-gain tilt sensors. The high-gain sensors provided high resolution, but a small dynamic range before going off-scale. The low-gain instruments yielded lower resolution but a greater range of measurement, and provided back-up should the high-gain system go off-scale. They also served as a redundant check of high-gain monitoring, an important factor in tilt monitoring (Dzurisin, 1992).

The high-gain tilt sensors are electrolytic bubble-type Applied Geomechanics model 800 at summit sites or model 701 at flank sites, with resolutions of 2.6 and 0.1 μrad/mV, respectively. Low-gain sensors have a resolution of 341 μrad/mV. The digital data telemetry platforms were designed and built by the USGS Cascades Volcano Observatory. Power is provided by automobile batteries coupled to solar panels. The tiltmetry systems are weather-protected, with radio communication provided by a planeless whip antennae within sealed PVC tubing. Analog inputs were digitized and transmitted by radio to the MVO receiving site at nominal 15-min intervals. Transmissions took less than 10 s, allowing several transmitters to share the same frequency. The tilt data were received by radio and relayed through the modem port of a computer for decoding and data

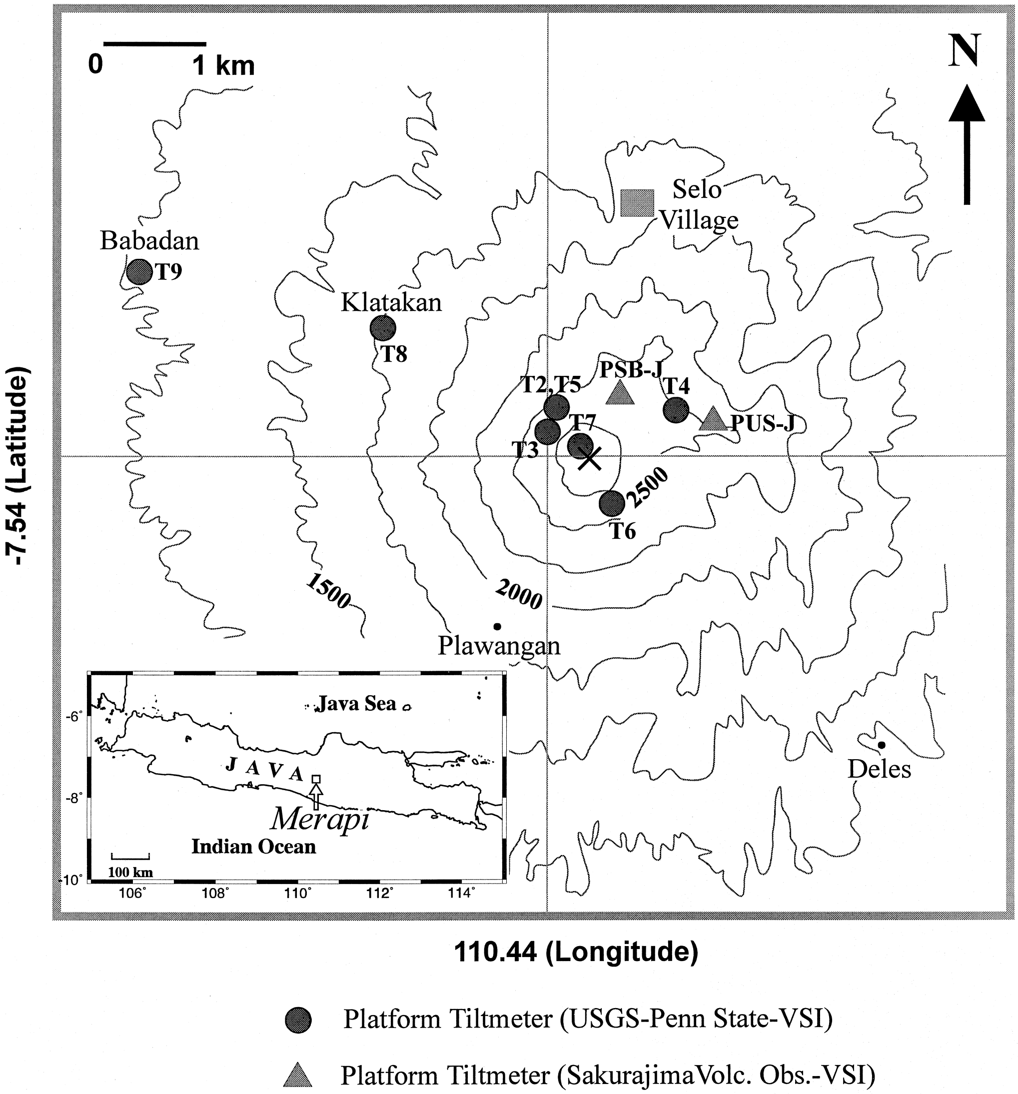
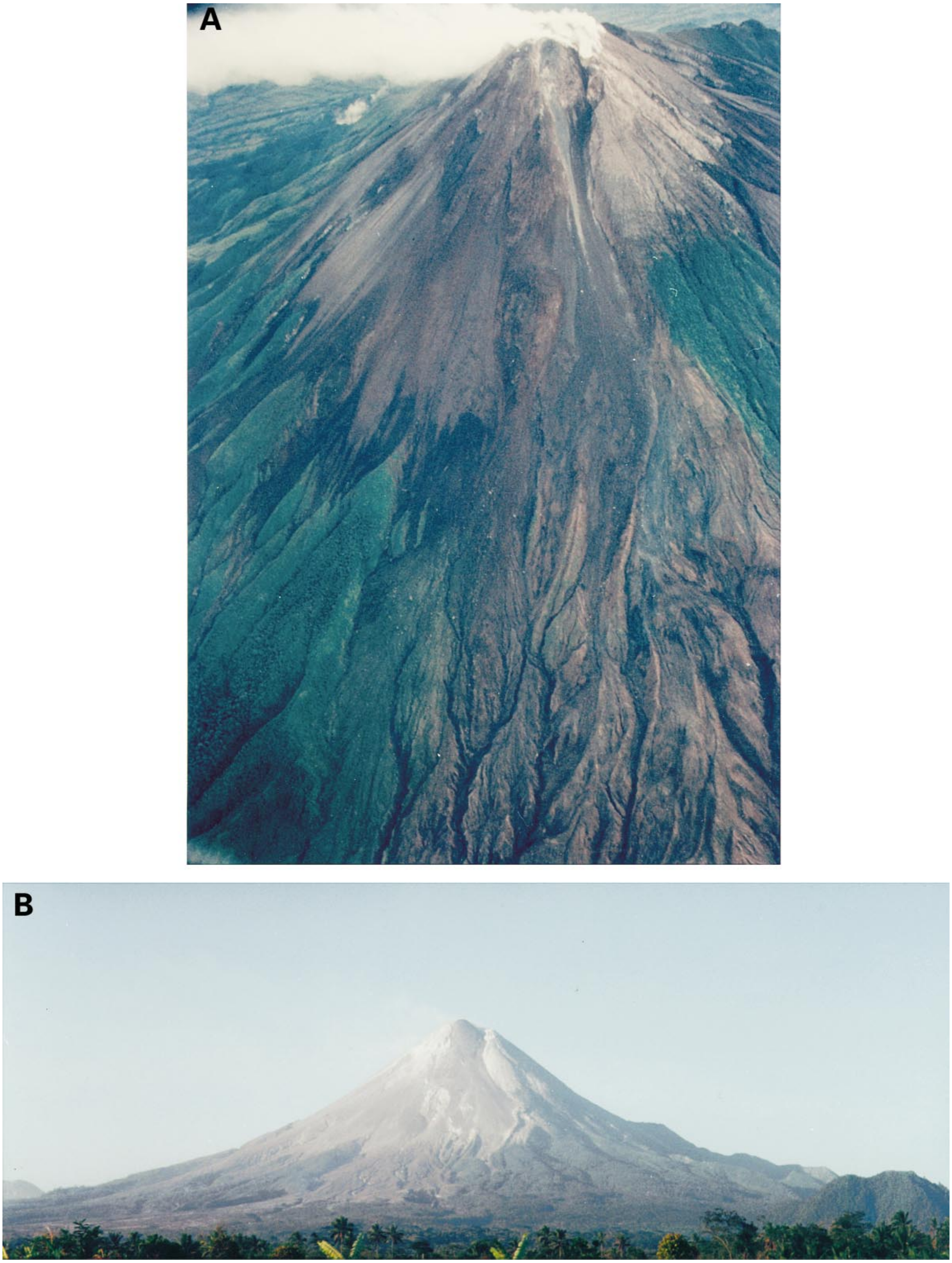


Fig. 1. Location of tiltmeters on Merapi Volcano. Contours at 500 m intervals. Inset map shows location of Merapi in Java. For other geographical references see Fig. 7.

storage. The data are stored in unfiltered form in a database but can be analyzed using the interactive, command-driven program BOB (Murray et al., 1996). For this paper the raw data were converted using BOB and processed to eliminate time gaps and noise spikes due to transmission problems. We decimated the tilt data by up to 24 times the original sampling rate to produce plots based on a sampling rate of 1 sample per 6 h. The tilt data are presented here exclusively as magnitudes for the radial direction, because the key stations utilized uniaxial instruments oriented to record radial deformation with respect to the center of the dome complex.

The number of tilt stations operating has varied through the time of this investigation (Fig. 1). Station locations at the summit have changed a number of times due to changes in dome geometry and reassessments of site quality. As many as four stations were operated along the northern crater rim proximal to the lava dome and its crater spillover point. Another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provided limited data on the upper south flank in 1993–1994. Vandalism problems have been minor, with maintenance and limited equipment availability the main problem issues in this harsh environment. A maximum of five summit stations (T2,3,5,6,7) were functional, in 1994. In 1995 three lower-altitude stations were added to the network by USGS and MVO, one (T4) in a concrete shelter on Pusunglondon ridge at radius from the summit about 1 km, ~2500 m a.s.l., another (T8) at a buried field site (Klatakan) at radius 2.4 km, ~1750 m a.s.l., and a third (T9) in a concrete underground bunker at the Babadan observation post, radius 4 km, ~1000 m a.s.l.

Over the period of time discussed in this paper the key summit station has been T3, with useful data for parts of this period also provided by T2. By January 1998, four tilt stations were operating within 4 km of the summit (T3,4,8,9) (Fig. 1). T2 has not worked since January 1998, and has sent no data to MVO on the high-gain channel since mid-1997. Unfortunately station T3, which had proven invaluable for hazard management, was destroyed by crater rim collapse in the buildup to the eruption of July 1998.

Previous studies of near-summit tilt (Young et al., 1994; Voight et al., 1994) suggested that renewed extrusion events since January 1992 had increased rapidly the total dome volume in six months. Dome growth generated gravitational collapses of small portions of the lava dome in the period 1992–1993. The tilt and other deformation data also suggested that a significant potential existed for future large-scale collapse, with impacts on a wider sector of the volcano. The eruptions from 1994 to 1998 revealed some of that potency.

3.2. Seismicity

During the period of investigation the seismic network operated by MVO comprised seven short-period seismographs with Mark L4C sensors (Ratdomopurbo and Poupinet, 2000 – this volume). Signals are transmitted by radio to MVO, where they are displayed on paper drums and also digitized with a sampling frequency of 100 Hz. Digital records are used for detailed analysis and hypocenter locations, whereas daily recording of event numbers and magnitudes are based on paper records. In addition RSAM and SSAM systems (Endo and Murray, 1991; Murray et al., 1996) provide real-time measures of seismic activity.

The classification of seismic events is discussed thoroughly by Ratdomopurbo and Poupinet (2000 – this volume). The event types are: (1) volcanotectonic A or VTA; (2) volcanotectonic B or VTB; (3) multiphase or MP; (4) low frequency or LF; (5) tremor; and (6) rockfalls (*guguran*, in Indonesian). Hypocenter depths for VTA and VTB are >2.5 and <1.5 km, respectively. MP and LF are emergent shallow events, characterized by dominant frequencies of 3–4 and 1.5 Hz; tremor generally has a frequency similar to LF events, and can last from minutes to hours.

Multiphase (MP) earthquakes were first recognized at Merapi by Shimozuru et al. (1969), and are related to the formation of the lava dome (Hidayat et al., 2000; Ratdomopurbo and Poupinet, 2000 – this volume). MPs occurred frequently during rapid dome growth. Their numbers decreased substantially when the dome growth occurred at a conventional rate (normal stage); the latter was characterized seismically by low occurrences of a few MPs, LFs, rockfall earthquakes per day, and a few VT earthquakes per week (Ratdomopurbo, 1991).

4. Activity at Merapi

Deformation and seismological studies are the most critical components in monitoring dome building and destruction at Merapi. In the accounts below we divide the analysis into periods that generally culminated in significant eruptions or periods of crisis. These periods are: (1) prior to 22 November 1994

Fig. 2. (A). Merapi viewed from high over southwest flank in February 1995. Extended gray area toward bottom of photo is region affected by nuées ardentes on 22 November 1994. Chute below dome points in southerly direction and explains why some nuée products were able to move south into the Boyong river drainage area (B. Voight photo). (B). Merapi viewed from 10 km southwest on 31 August 1994. The large accumulation of 1994 dome lava collapsed piecemeal on 22 November, generating nuées ardentes that moved to the southwest, and also southward (to the right) into the Boyong drainage. Turgo Hill at lower right (MVO photo).

dome-collapse; (2) the more or less stable growth of 1995; (3) the crisis in October 1996; (4) the vulcanian explosion of January 1997; and (5) the eruption of July 1998. Monitoring data are discussed in relation to observed activity, and aspects of volcano hazard management are also examined.

4.1. November 1994 dome-collapse catastrophe

In February 1994 fresh lava emerged at the SW edge of the 1992–1993 dome, and extrusion caused disruption and small-scale collapses, leading to glowing rockfalls and short (<1.5 km) nuées ardentes. Tilt switched from inflation to deflation during this period of exogenous growth. By May lateral and vertical dome growth had accelerated, pyroclastic flows ceased, and long-term inflationary tilt began and persisted to 22 November. MP seismicity appeared 25 April, and about at this time small-scale rockfalls declined in number and became less incandescent, suggesting cooling and hardening of the lava crust. A rounded, apparently more stable lava carapace had developed. The flux between April and August averaged about 17000 m^3/day (Ratdomopurbo and Poupinet, 2000 – this volume). By early September the new dome was 47 m high with a volume of about 2.6 million m^3 (Figs. 2B and 3A). Numerous MP earthquakes occurred, with the peak rate in May about 80 events per day, declining to about 20 events per day in August (Fig. 4). By late August, the rate of rockfalls sharply dropped. Photographs in August and September showed little exterior morphologic change, although tilt and MP seismicity suggested continuation of growth at a small rate, with volume lost by rockfalls much less than the volume added (Fig. 4). The SO_2 flux from COSPEC was roughly 100 tonnes per day for the first half of the year, declining to about 70 tonnes per day after July. The dome interior was highly crystalline but may have contained a small melt fraction (Hammer et al., 2000 – this volume) and the dome was metastable. The last alert communication from MVO to the local regencies was issued on 4 November, on the basis of LF earthquakes since 20 October and a tremor episode on 3 November, although the significance of these observations was uncertain (Sukhyar, 1995; SEAN, v. 19(12)). During 21–22 November, a team from MVO ascended the summit to make dome observations, monitor fumarole gas, and to install a crack extensometer.

On 22 November, while the MVO team was on the summit, the first nuées ardentes began at 1014. Further nuées ardentes followed in succession (Fig. 5), and at 1025 MVO instructed all observation posts and radio stations of the Regional Task Force (SATORLAK) that the alert status had been raised to the highest level (IV) and that evacuations should begin. Another evacuation warning was radioed to regional task forces at 1100 (SEAN, v.19(10)), but by then the largest and most damaging nuée ardente had occurred (Fig. 6).

Direct warnings to the population were ineffective because the traditional hollow-log drum ("tong-tong") at the crucial Plawangan observation post was in disrepair, even though higher technology devices such as sirens had not been installed (Voight, 1996, p. 761). Ultimately about 2.5 million m^3 of the dome (nearly all the 1994 lava) collapsed over 7 h in a series of energetic pyroclastic flows and surges, devastating the south and southwest flank as far as 6.5 km from the summit (Fig. 5–7, 2A; cf. Abdurachman et al., 2000 – this volume; Brodscholl et al., 2000 – this volume). Over 60 persons were killed and dozens more suffered serious burn injuries in the village of Turgo and the edge of Kaliurang (Shelley and Voight, 1995). The Plawangan post was abandoned temporarily and moved to Kaliurang.

The collapse was not preceded by any significant short-term seismic precursor (Ratdomopurbo and Poupinet, 2000 – this volume). Likewise tilt indicated no clear short-term precursor (Fig. 4) although interference problems, apparently due to continuous transmission at tiltmeter T6, blocked the acquisition of other high-gain tilt data for 34.5 h prior to the collapse. No data could be recovered from other high-gain stations in this period. Five tiltmeters were operative over this period, including the cluster T2, T3, and T5 on the northwest rim, T6 on the south flank, and T7 on the dome in 1992–1993 lava. Over the long term, on average 3.5 μrad/day inflation had occurred on T3 over 210 d (Fig. 4), with lesser amounts at T2 and T5. T6 provided limited data but, along with others, showed no clear precursor. T7, on the dome, displayed tilt changes an order of magnitude greater than other sites. Prior to the eruption a steady inflationary tilt at T7 of about 32 μrad/day was

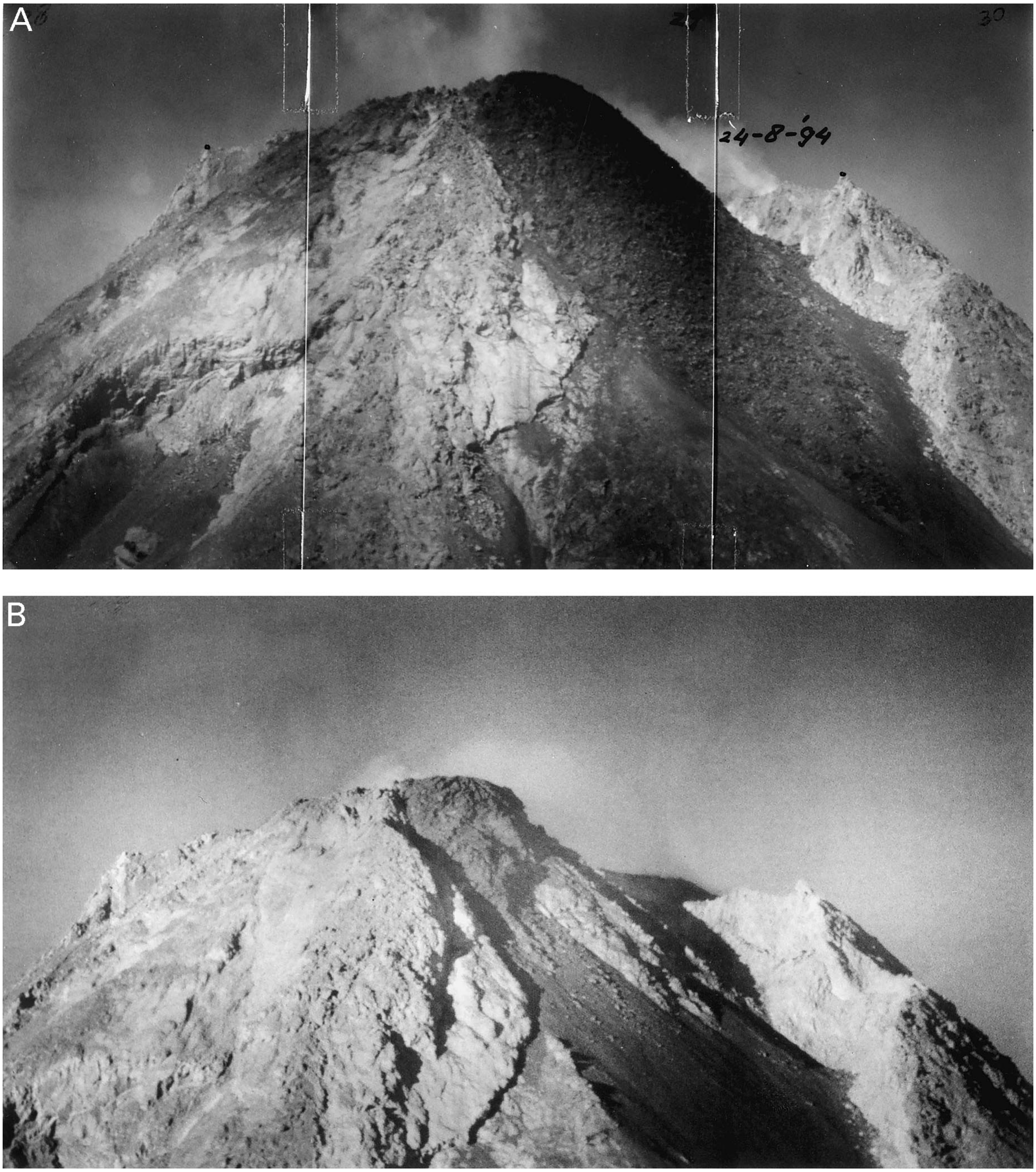


Fig. 3. Detailed views of lava dome from 12 km southwest (Ngepos post). (A). View on 24 August 1994, showing 1994 lava that collapsed on 22 November 1994. (B). View in May 1996. A similar appearance was noted in December 1995, after the 1994 dome had collapsed in November.

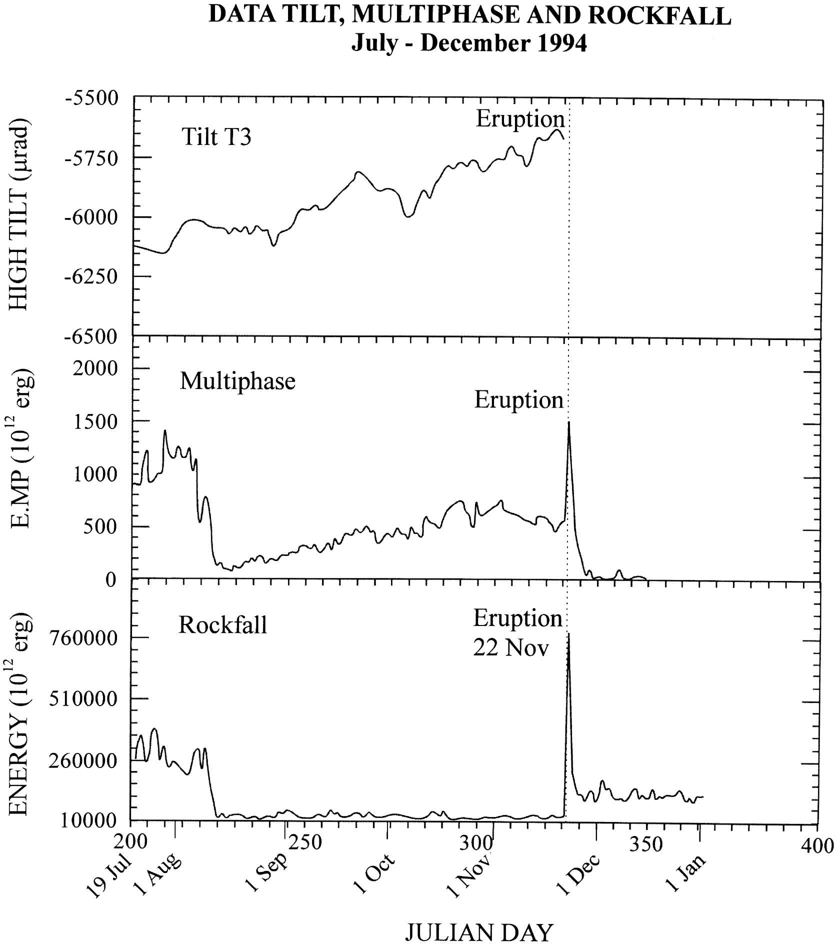


Fig. 4. Monitored data in relation to the lava dome collapse of 22 November 1994. Data shown are high-gain tilt at summit station T3, MP earthquake energy, and rockfall energy.

recorded, with a hint of an increase on 20 November. Deflationary tilt then developed at this station, with the onset of deflation occurring sometime during the data gap. During the 4.2-d gap, T7 deflated about 1000 μrad, and between 25 and 31 November the deflation rate averaged −36 μrad/day. About 35 MP events/day had occurred over the long-term buildup (Fig. 4). Many rockfalls (~16,000) were observed during this overall period.

Continuing small collapses through 7 December sent small nuées up to 1.5 km long toward the Boyong (Fig. 8). Most of the >6000 local evacuees were allowed to return home in early December, but local authorities decided that 2700 evacuees from five villages within about 6 km of the summit in Sleman District would be resettled locally (SEAN, v.19(12)). Residents along the Code River (15,000 people in 11 villages) in Yogyakarta were alerted to the possibility of evacuation due to expected rain-triggered lahars from the Boyong River.

4.2. 1995 Stable growth

In 1995, deformation was detected by two or three tiltmeters operating at the summit plus several others on the flank. Changes from inflation to deflation occurred sequentially from distal to proximal sites, suggesting a shoaling pressure source.

No nuées ardentes with significant runout (>2 km) occurred in 1995, although lahars were generated by rain-mobilization of the 1994 pyroclastic deposits. The T3 tilt pattern during 1995 showed general deflation until mid-June. It then experienced inflation that carried into 1996 (Fig. 9).

In the period April 1995 through March 1996, the number of seismic events was dominated by MPs. These MPs had small amplitude compared to LFs whose occurrences were second in number after MPs. The seismic energy produced by LFs was larger than the seismic energy of MPs (Suharna, 1996, personal communication). Small collapses producing glowing rockfalls were reported in January and August–October 1995 (SEAN, v.20(2,10)) and in November 1995.

4.3. October 1996 crisis

The condition of the lava dome in May 1996 is shown in Fig. 3B. With further dome growth, on 9 August 1996—following a generally steady increase of tilt recorded at four or more stations since February (T3, T2, T8, T9, Fig. 10)—a nuée ardente generated by dome-collapse flowed as far as 3.5 km to the upper reaches of the Krasak and Boyong rivers on the SSW flank. No casualties occurred. No volcanic earthquakes had preceded the collapse of the 1996 lava, and only about 10^5 m^3 of 1996 lava remained. A burst of low-frequency (LF) earthquake energy was released by mid-August, and after the second week of September, MP events sharply increased to 1400 events/day (Fig. 10). The dome volume was estimated at 4.5×10^5 m^3, and 7.5×10^5 m^3 on 24 September and 11 October, respectively, based on Celestron telephotographs. Lava flux was ~17000 m^3/day, compared to a "normal" flux about 3000–5000 m^3/day.

Meanwhile the MP earthquakes increased enormously, exceeding 3000 events over a 12 h period on 24–25 October (Fig. 10). The overlapping MPs evolved into a harmonic tremor-like pattern not previously recognised at Merapi, given the name "batik-quakes" by the local staff. Four nuées ardentes occurred on 24 October with 2.5 km runout to the SSW.

At this point, after a series of consultations with the Director of VSI at Bandung, the status of Merapi was raised from level II (*Waspada*), "attention," to the third alert level (*Siaga Merapi*), "standby." By 29 October the dome volume was 1.1 million m^3, dome height was 48 m, and distance between dome top and toe of the lava tongue was 210 m. The summit tiltmeters recorded a general inflation from 9 August to late October, consistent with the increasing seismicity and nuées ardentes activity; e.g., T2 increased by ~310 μrad. A few small nuées ardentes occurred on and after 28 October, and on 31 October at 1544, after a heavy summit rainfall, activity reached a peak. A series of 17 nuées began flowing down the southern flanks, toward the Kuning and the Bebeng drainages, and their runout distances grew to about 3 km.

After this, the Head of MVO asked the local government of Srumbung district to evacuate alluvial sand-and-gravel quarry workers in the southwest riverbeds to safer sites. Then at 1645 the alert level, for the populated Boyong River only, was raised from *Siaga Merapi* to *Awas Merapi* (level IV, "evacuation") by the Head of MVO, with the Director of VSI kept informed continuously by portable telephone. The local population was alerted by siren, and the responsible government hazard management authority (SATORLAK) was alerted by communications radio on the emergency channel and by redundant systems using telephone and facsimile messages. SATORLAK then evacuated about 20–30 families (about 100–200 people) from the Boyong River area near Kaliurang to the refugee camp for one day (Subandrio, written communication based on information given by Panut at Kaliurang VSI Post). Villagers in Turgo and Tritis moved willingly, but soon afterward returned to their houses. During this time the Head of Sleman Regency, who was also the Head of SATORLAK, was in Kaliurang giving the order to move to the refuge.

From 1718 to 2117, seismic information revealed that nine small nuées ardentes occurred, then between 2130 and 2352, seven moderate nuées descended the S and SW drainages, with none exceeding 3 km. Nuées ardentes decreased the next day and ceased by November 2. The number and energy of MP earthquakes also sharply decreased (Fig. 10), although rockfalls increased slowly to >100 events/day. Based on this information the alert level was reduced to standby, *Siaga Merapi*.

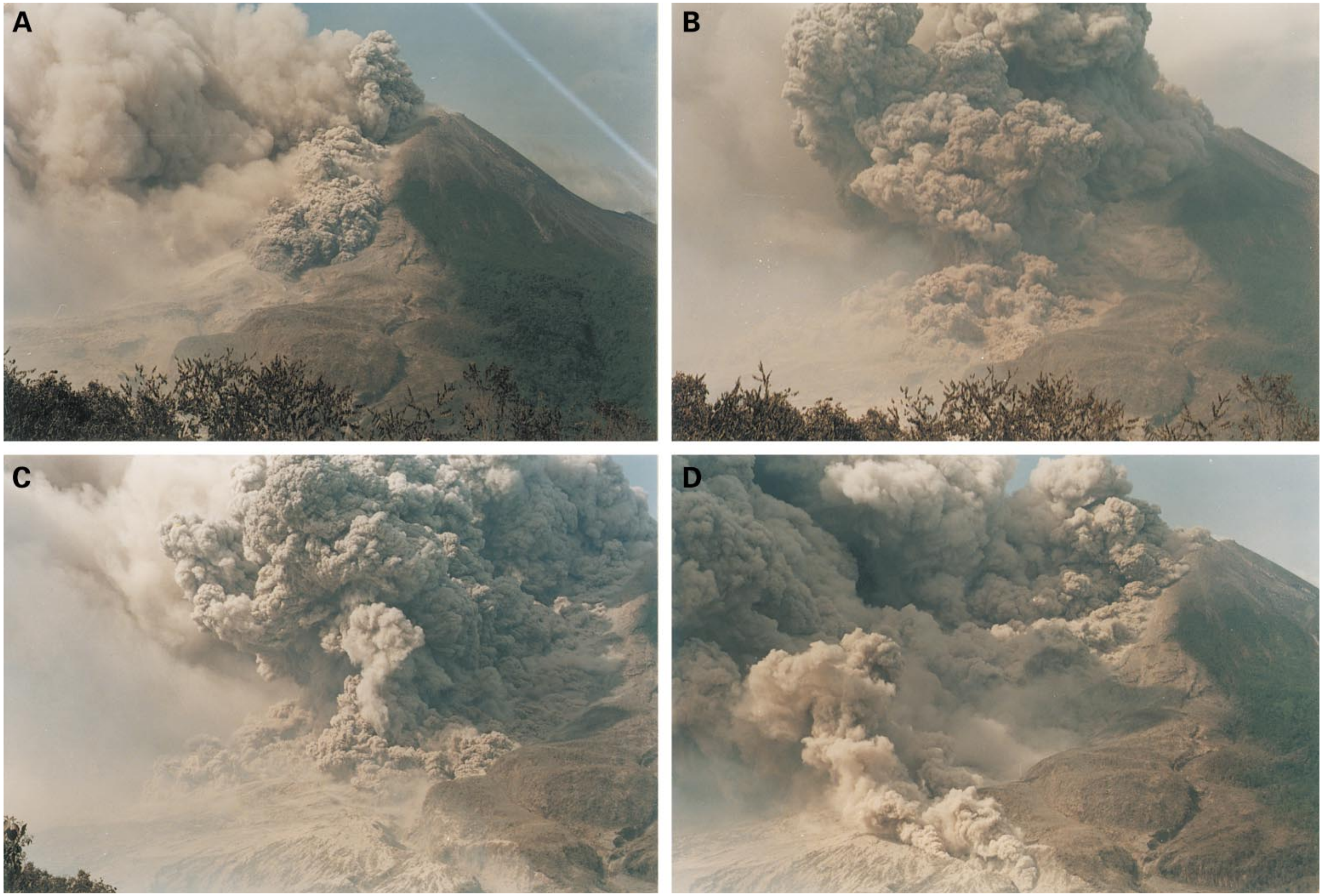


Fig. 5. Nuées ardentes on 22 November 1994. (A,B). Initiation of small nuées around 1430 (Panut photos, from Plawangan post on the south flank; Fig. 7). (C,D). As above; nuée ardente descending (C) toward and (D) into steep-walled channel. Dense basal part of nuée enters the channel and is deflected to the southeast. (E,F). Co-ignimbrite ash clouds associated with nuées as viewed from Jrakah post, near Selo on the northwest (Dewi Sri Sayudi photos).

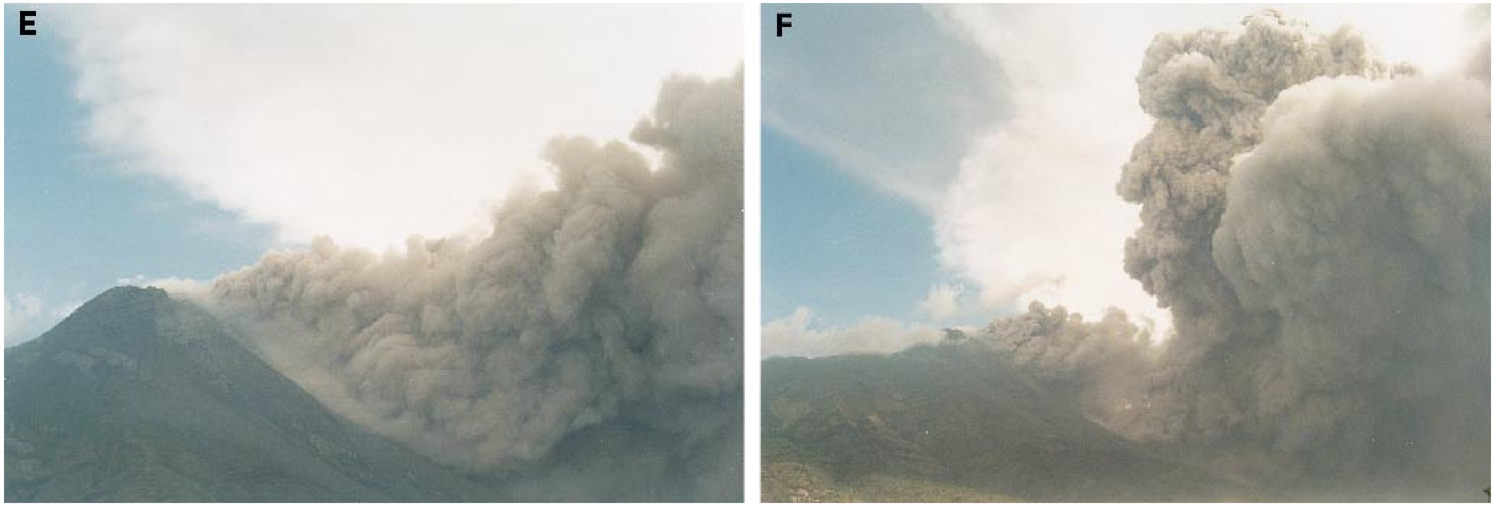
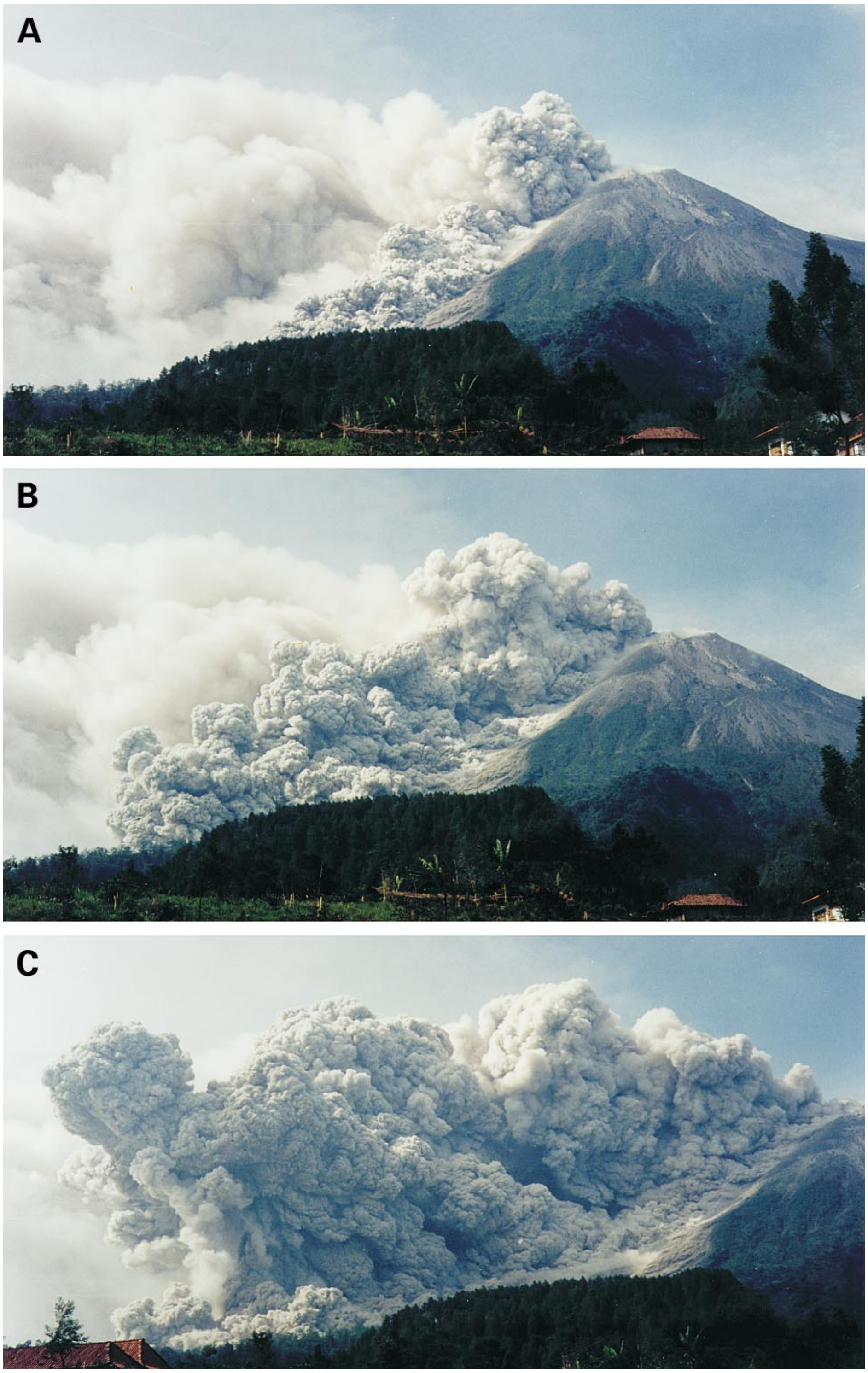


Fig. 5. (*continued*)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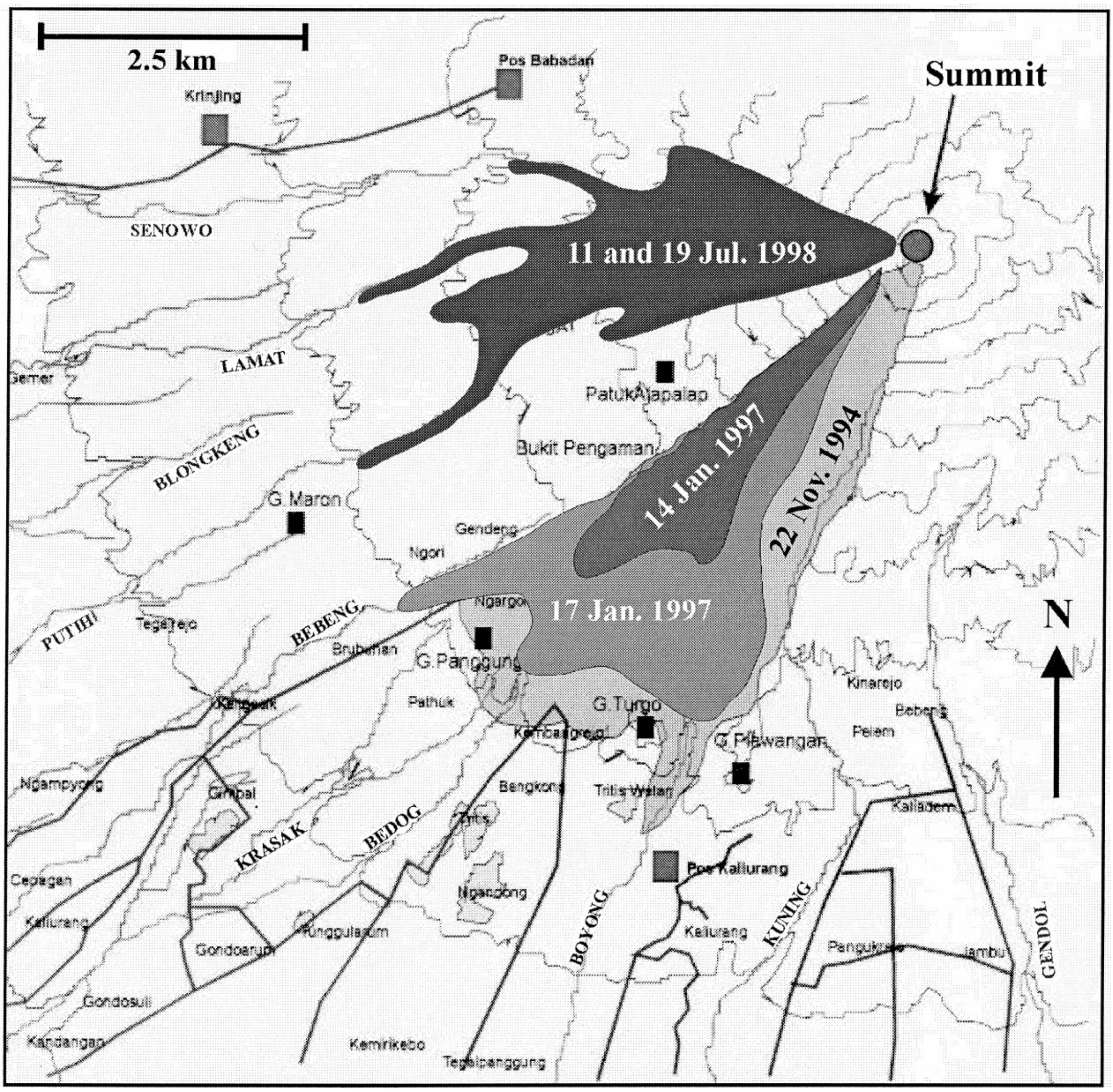
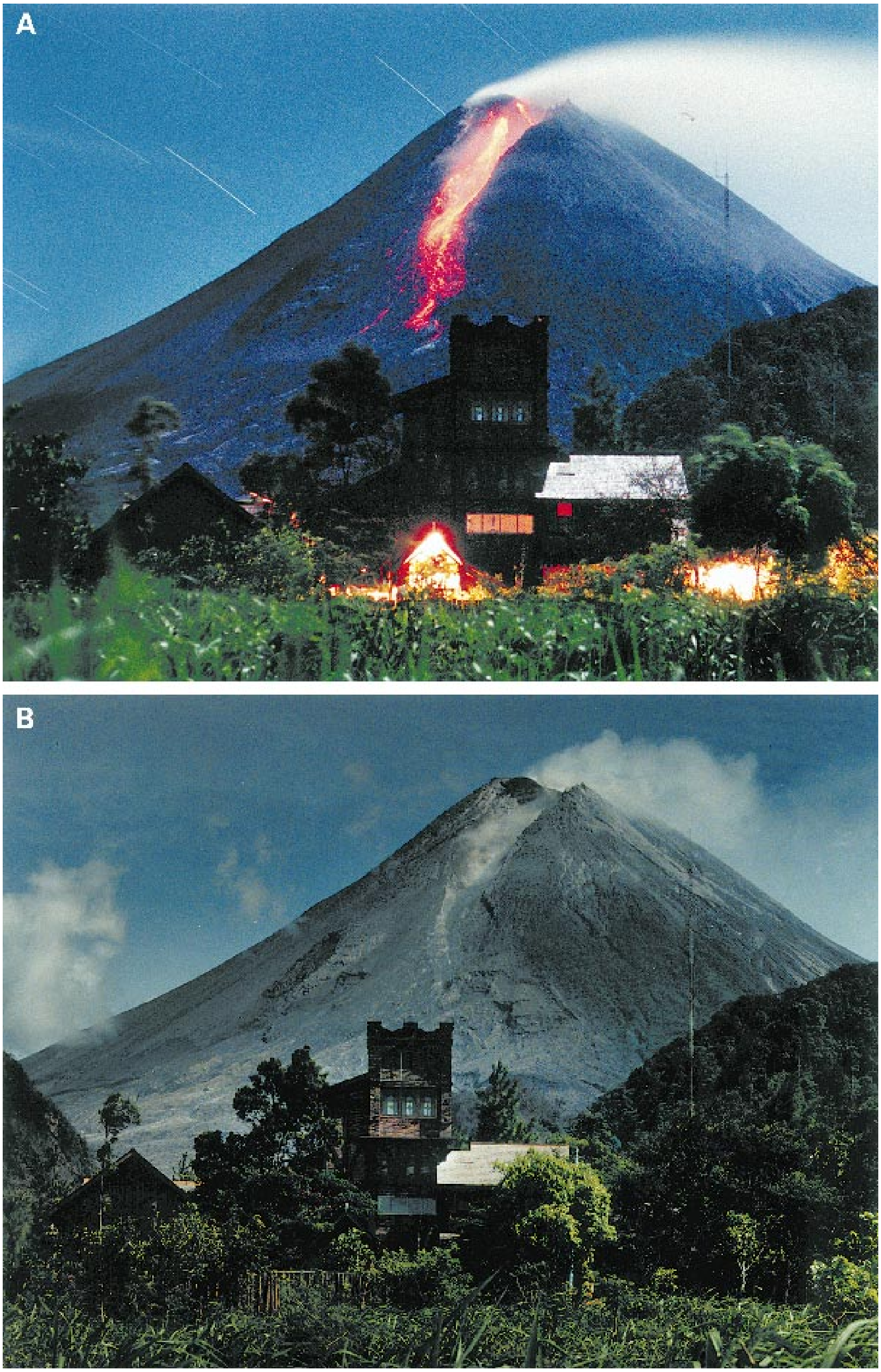


Fig. 7. Major nuée ardente deposits of 22 November 1994, 14 and 17 January 1997, and 11 and 19 July 1998 on the southwest flank of Merapi.

4.4. January 1997 vulcanian explosion

The dome volume was $\sim 8.5 \times 10^5\ m^3$ in mid-November 1996 and the same value was calculated in mid-December. MP seismicity had virtually ceased (Fig. 10), and both lack of MPs and the volume calculations suggested a virtual absence of dome growth. However the rate of tilt inflation remained steady

Fig. 6. Nuée ardente sequence as viewed from Kaliadem (see Fig. 7). Time about 1400–1500, 22 November. View to the northwest, with the nuée ardente descending into the Boyong drainage area (M. Mongin photo).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during November and then began to increase rapidly during December and into January (Fig. 10), suggesting an accelerating buildup of pressurization. By late December, glowing rockfalls were being shed toward the southwest drainages, but some were able to move southward toward the Boyong (Fig. 11).

On 7 January, after a two-month absence, over 100 MP earthquakes were recorded, and over 500 MPs occurred on 11 January. The cumulative energy release for all volcanic earthquakes (but primarily due to MPs) built steadily to 13 January (Fig. 12A). Meanwhile the inflation at T3 had already accelerated (Fig. 12B) and by 13 January was ~200 μrad/day. The alert was raised to level II, *Waspada Merapi.* Tilt inflation continued through 14 January, when at 0930 the first of many dome-collapse nuées ardentes occurred. During the next 10h 81 nuées rolled down the SW flank, with runout as far as 4.5 km (Fig. 7), and the alert was raised to level III, *Siaga Merapi*. Also on this day, a swarm of 35 shallow volcanic earthquakes (VTB) occurred, with a high energy-release that caused a jump in the cumulative seismic energy plot of Fig. 12A. Over 300 MPs also occurred on 14 January, releasing significant energy but still only about 1/6 of that from the VTBs.

During the next two days, the rate of MPs declined, tilt inflation peaked and slight deflation occurred (Fig. 12). Then a sudden increase of MPs occurred over a 10-h period that culminated in a vulcanian explosion at 1035 on January 17, producing a 4-km-high plume (Fig. 13). High-frequency tremor had appeared one hour before, and continued until, the explosion (Ratdomopurbo and Suharna, 1997). The center of the explosion was situated on top of the active “1996 dome,” and a small crater was created that faced southwest, completely enclosed by 1996 lava. A new dome grew in the explosion crater, accompanied by MP earthquakes, which then dominated Merapi activity in 1997.

The explosion was heard in Yogyakarta, 35 km to the south. The mushroom-shaped plume generated a nuée ardente by fountain-collapse, which descended the southwest flank as far as 6 km. The area devastated was comparable to that of 22 November 1994 (Fig. 7); runout was slightly longer on the Bebeng, but less on the south. Fortunately the Boyong river narrows near Turgo and Kaliurang villages was unaffected in 1997, although the Boyong drainage area north of the narrows had been struck by the nuée ardente.

Another explosion was reported in the morning, and others at 1345 and 1600. The alert level was raised to IV (*Awas Merapi*) at 1045 on 17 January, 10 min after the explosion. Based on the standard procedure following the *Awas* alert, SATORLAK immediately evacuated most residents living near the Boyong River. Indonesian newspapers reported 8000 people were evacuated from regencies of Sleman, Klaten, Boyalali, Magelang and Yogyakarta, but also that a number of people had defied the evacuation order. Workers collecting river sands for construction (numbering several tens of people) in Bebeng and Krasak riverbeds initially did not want to evacuate; but because the eruption occurred during the day, and was announced by radio communication, they finally evacuated without use of force (Subandrio, written communication). Volcanic activity decreased on January 18, MP activity continued to decline, and tilt deflation generally continued. On January 23 the alert level was reduced to III, although on the following day 13 nuées ardentes were recorded with runout to 4 km. Many evacuees returned home around this time despite the warnings. According to local news media, in the January events six people were missing and several were injured.

4.5. July 1998 eruption

A relative calm in seismic, deformation, gas, and rockfalls ended in June 1998, with the locus of activity switching from the southwest to the west part of the dome complex. Changes in measured tilt began in June and accelerated strongly at the end of the month (Fig. 14). The tilt at station T3 on 1957 lava

Fig. 8. Merapi from the south in Kaliurang village, December 1994. (A). Night photo at 0300, showing incandescent rockfalls descending southward into the Boyong drainage. Star-traces indicate exposure time. (B). Morning photo at 0830. Small dome of fresh dark December 1995 lava at summit. Chute below dome carries rockfalls toward the south (cf. Fig. 2A). Lower south and southwest flank devastated on 22 November 1994 (H. Wiyanto photos).

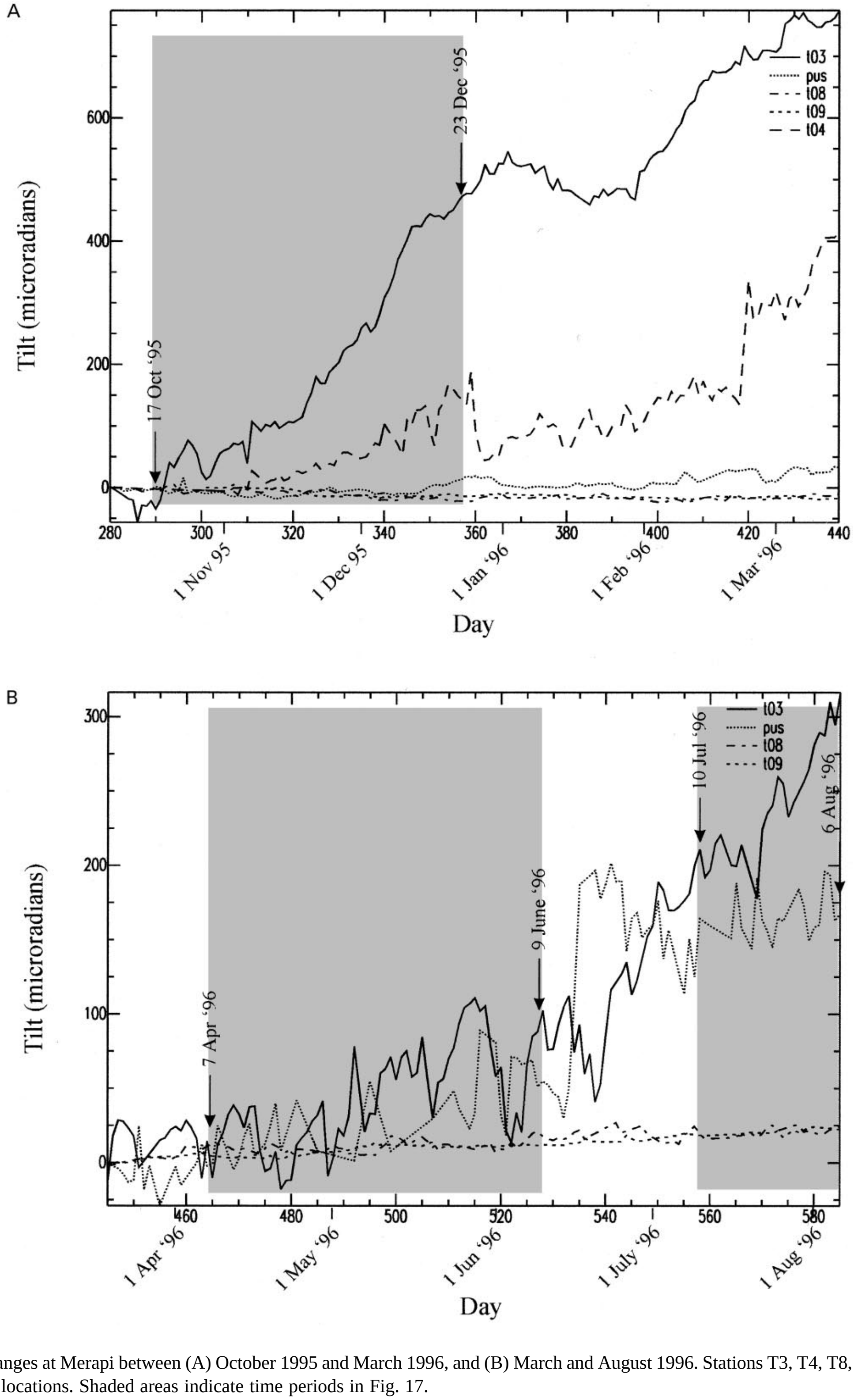


Fig. 9. Tilt changes at Merapi between (A) October 1995 and March 1996, and (B) March and August 1996. Stations T3, T4, T8, T9, and Pus-J; see Fig. 1 for locations. Shaded areas indicate time periods in Fig. 17.

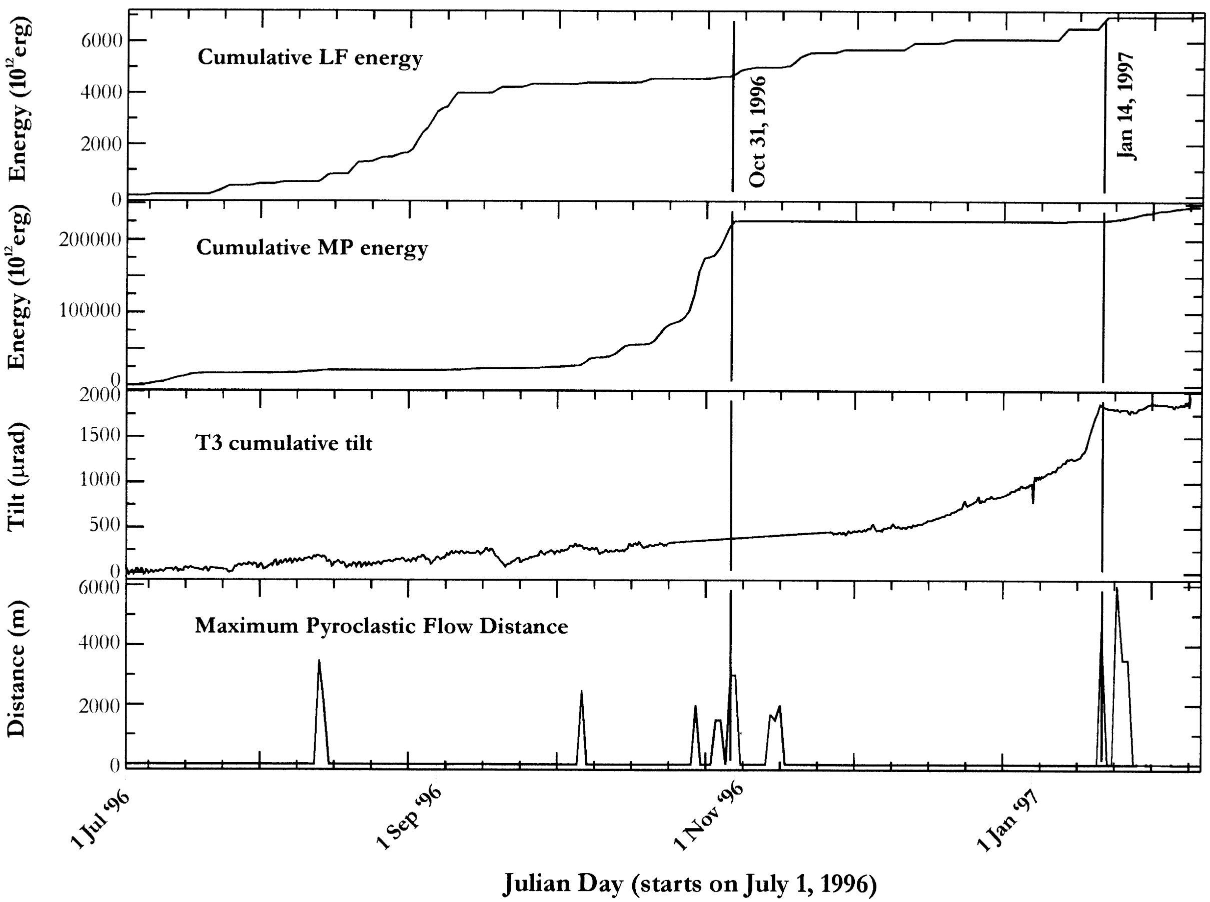


Fig. 10. Monitored data in relation to the crisis of 31 October 1996 and the eruption of 14 and 17 January 1997. Data shown are cumulative LF energy, cumulative MP energy, T3 cumulative tilt, and maximum pyroclastic flow distance. Note that for the 14 January eruption, tilt is the most diagnostic precursor.

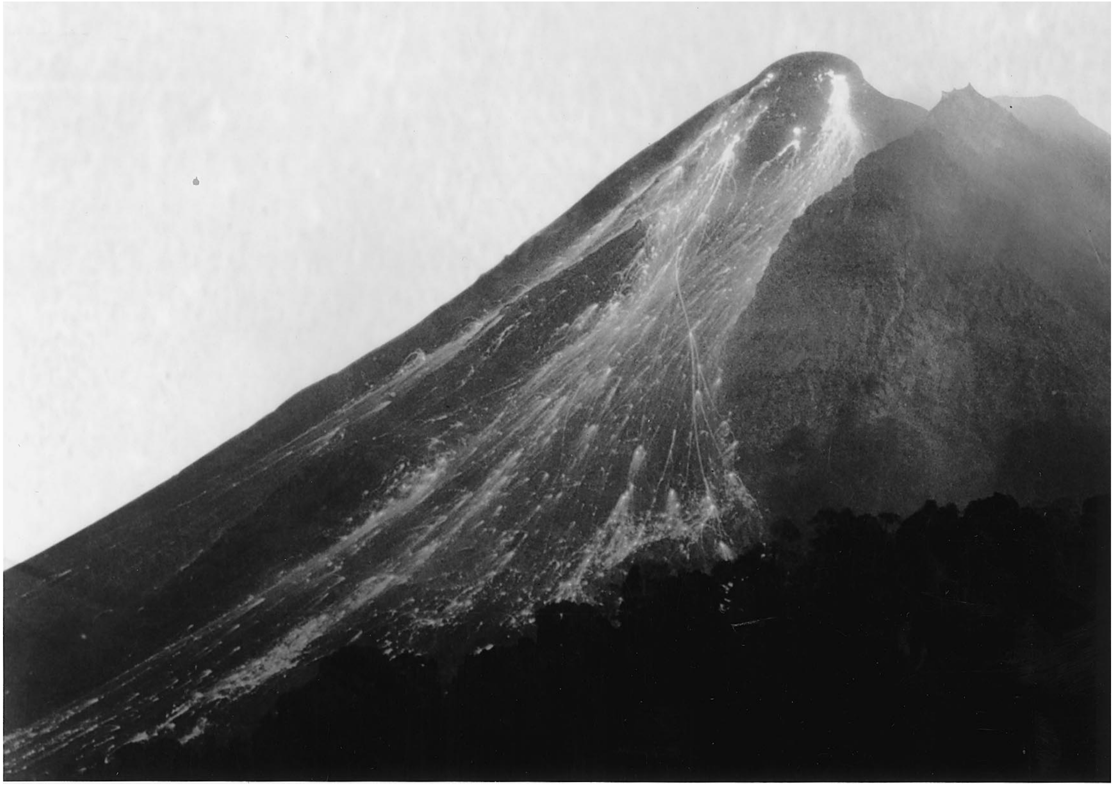


Fig. 11. Incandescent rockfalls (guguran) from the lava dome on 28 December 1996, from the Kaliurang post south of the volcano. Rockfalls were scattered over a large sector, from the Bebeng and Krasak rivers of the southwest, to the Boyong and Kuning rivers on the south. Fortunately the large nuées ardentes on 14 and 17 January did not travel far enough southward to reach populated areas (Fig. 7).

showed extraordinary rates after 29 June, from ~14 μrad per day to 150–200 μrad per hour (compared to 200 μrad per day, in January 1997). SEAN (v. 23(8)) reported that this tilt was a false value, influenced by heat radiated by the new dome. However, the SEAN interpretation is unlikely as the tilt change was recorded independently by both high-gain and low-gain sensors between 29 June and 3 July, when the high-gain sensor went off-scale at ~19,500 μrad. We regard the tilt change as reliable but indicative of an unstable part of the crater rim. The low-gain sensor continued to deform at similar rates until 8 July, when it was destroyed in a collapse of the crater wall and adjacent lava, generating a rockfall or nuée ardente (Fig. 14). Over the same period, tilt changes were also recorded at other sensors, including ~7 μrad at the underground station T9 at Babadan post, 4 km west of the summit.

The increased tilting was followed by increases in shallow volcano-tectonic (VTB) events, and in MP seismicity generally attributed to dome building. There were 33 MPs from 15 to 21 June, and 45 MPs from 22–28 June; their number increased sharply after 1 July, with 925 between 29 June and 6 July, and 2029 between 7 and 12 July (Fig. 15). During the same four periods the numbers of VTB earthquakes were 4, 3, 47, and 21, respectively. A small explosion on 30 June had generated a plume over the summit and a small nuée ardente on the west slope, and opened a hole on the west slope near the summit. New glowing lava was squeezed from the opening “like toothpaste” (SEAN, v.23(8)). Lava rockfall-avalanches (gugurans) connected with new dome growth increased dramatically, and were observed from the west-flank post at Babadan (Fig. 15). The rockfalls originated not only from new lava and surrounding 1992–1997 lava, but also 1934 lava. Their descent was directed principally toward the

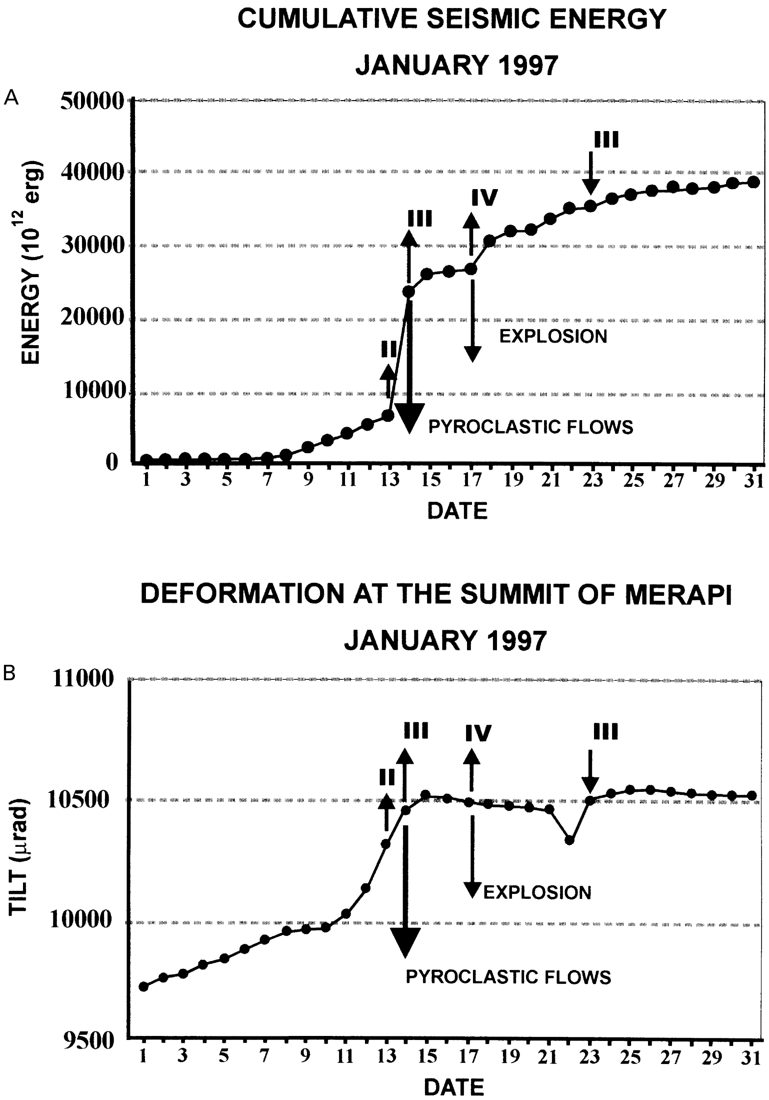


Fig. 12. Monitored data in relation to the eruption of 14 and 17 January 1997, and alert levels as discussed in text. (A). Total cumulative seismic energy (sum for MP, LF, VTA, VTB events) against date. The plot mainly reflects energy of MP events, except for the jump on 14 January, due to a VTB swarm. (B). High-gain tilt at T3 against date (cf. Fig. 10).

Senowo river drainage, and to a lesser extent towards the Lamat, Blongkeng, Sat and even the Krasak/Bebeng and Boyong drainages. As a result of the tilt, seismicity, and rockfall observations, the alert was raised to level II (*Waspada Merapi*) at noon on 2 July.

The activity was being monitored from MVO in Yogyakarta, with visual information supplied from the flank posts at Babadan and Plawangan. On 7 July the response team that had been formed to evaluate the crisis went to Babadan to make intensive visual observations and to conduct EDM measurements to fixed reflectors high on the northwest flank (Young et al., 2000 – this volume). Only one of the three reflectors could be located at midnight. Subandrio reported (written communication): “The result was very surprising; there was a contraction of about one meter. Soon after the measurement there was quite a large rockfall that originated from above

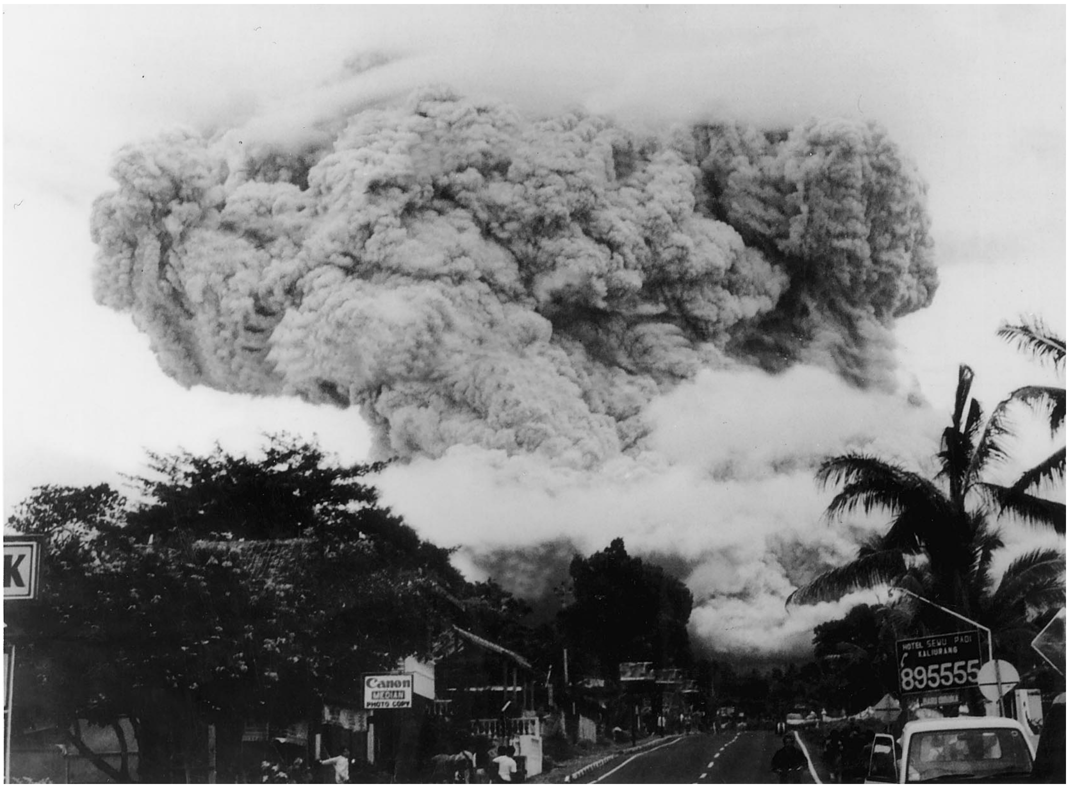


Fig. 13. Plume of 17 January eruption as viewed from Pakem, south of Kaliurang (Subronto photo).

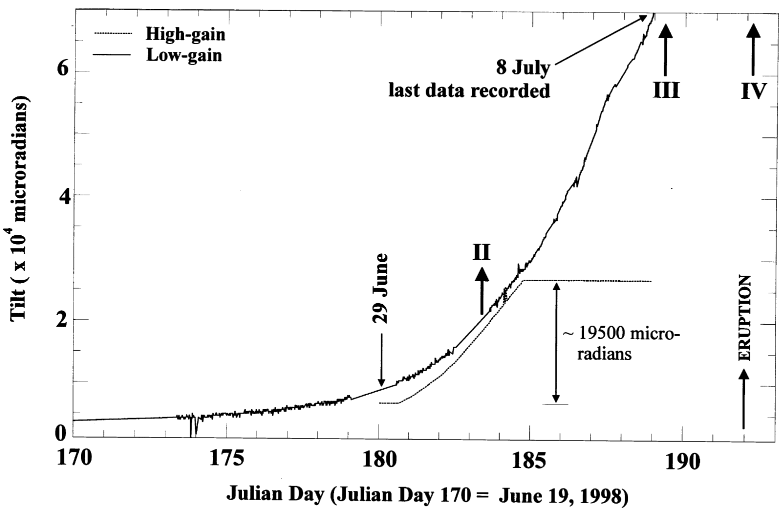


Fig. 14. Tilt against time in Julian days, beginning 19 June 1998, and alert levels as discussed in text. The high-gain sensor went off-scale after 19500 μrad. The low-gain sensor continued to deform at high rate until the tilt system was destroyed in a partial collapse of the crater rim. The eruption occurred 3 days later on 11 July.

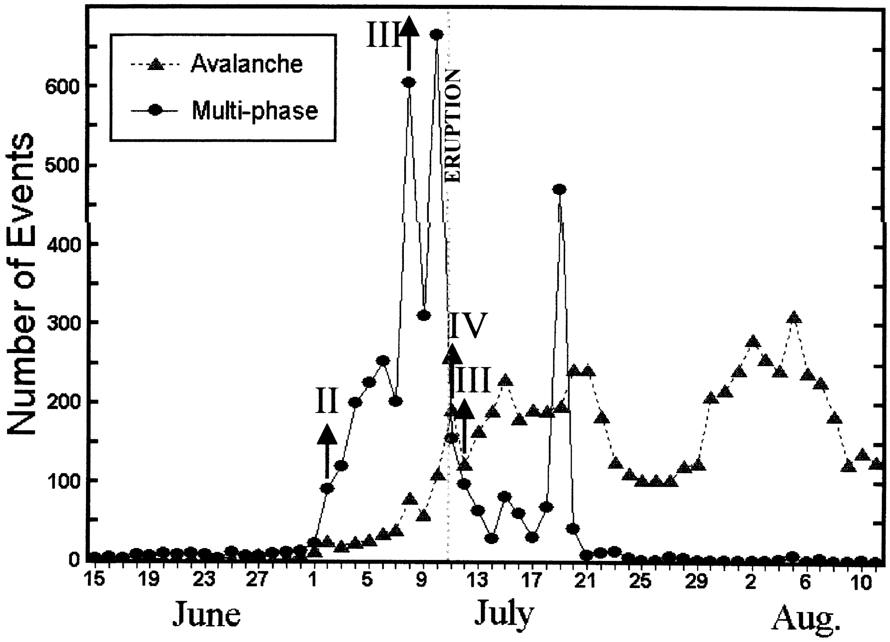


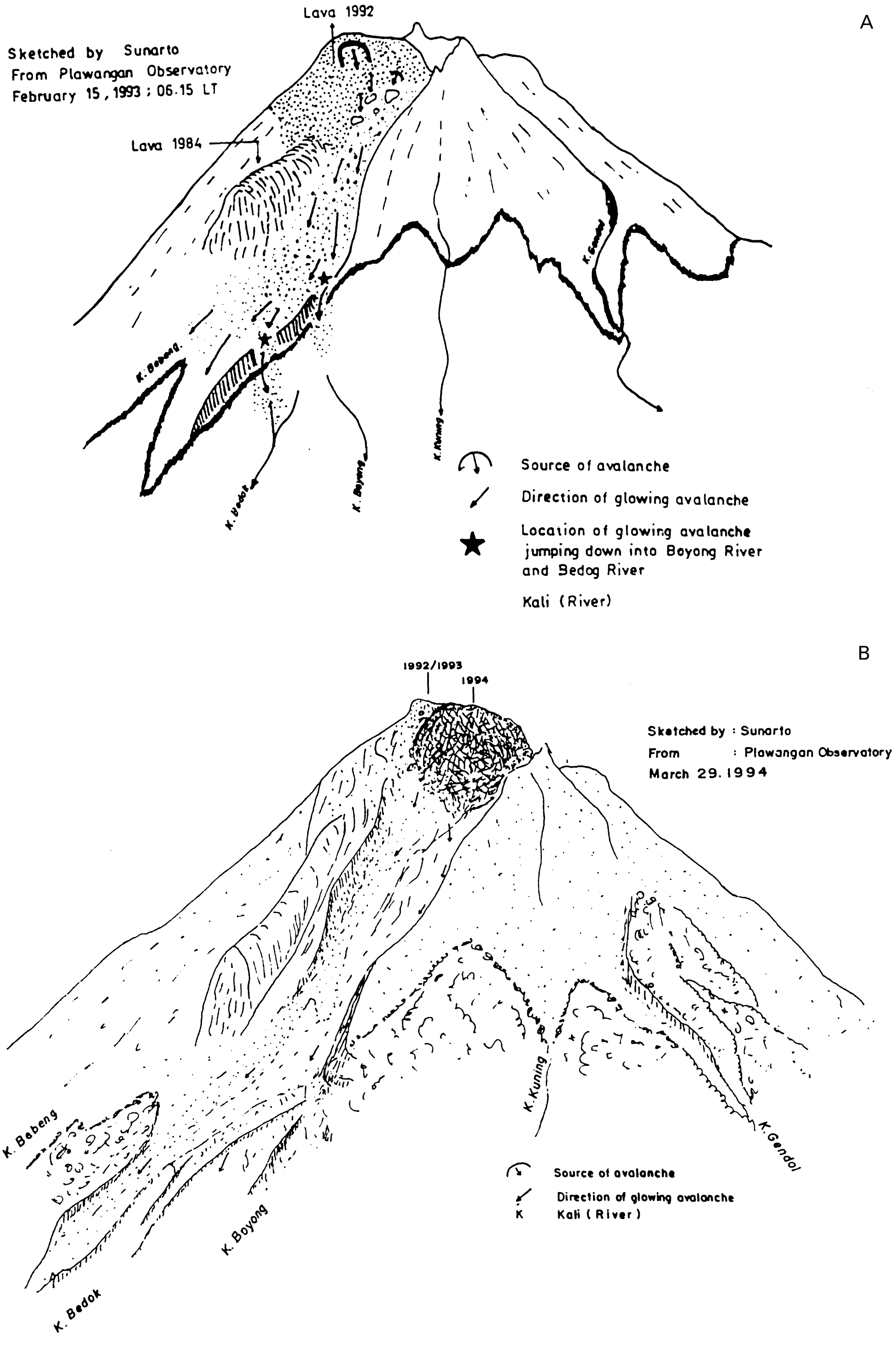
Fig. 15. Numbers of rockfall (avalanche) events and MP earthquakes recorded at Merapi during 15 June–12 August 1998. Alert levels as discussed in text.

1957 lava, and then the reflector was no longer visible due to heavy dust cloud. Later that morning I went to Yogya to see data from station T3, which was still rapidly increasing. The rockfalls were heading west, filling the head channels of the Lamat, Blongkeng and Sat rivers, and sometimes Senowo II. At about 0330 after Renaldo scored a goal (we were watching the semifinal of the World Cup), a small pyroclastic flow occurred. I contacted the office to see data from T3, but unfortunately the telemetry system was no longer transmitting data; the last data was received at 0045. I concluded the edge of 1957 lava had collapsed, and after reviewing the EDM data concluded that 1957 lava was unstable. At 0445 I contacted the Head of MVO and advised raising the alert level". The alert was raised to level III (*Siaga Merapi*) at 0500 on 8 July, indicating that residents should prepare for evacuation.

Early on the same day the new lava dome could be clearly observed from Babadan, with its position close to 1997 lava. Later observations showed that the new lava had emerged through the northwest half of the 1997 lava dome, and had developed a rounded shape with flanking slopes about 45°. Pressurized gas emerged from the upper part of the dome. Observations from Jrakah post on 9 July showed a V-notch near the top of dome 1997 that may have been a source for rockfalls or nuées.

Seismicity continued to build with MP activity at ~60 events per hour, and six shallow VTBs occurred on 10 July. Rockfalls of various sizes descended westward, and peaked in the early morning of 11 July with the generation of 36 nuées ardentes. The large nuées began at 0131 with runouts to 3 km on the Lamat headwaters, and plumes rose as high as 4.8 km above the summit. At 0240 a nuée ran out to 4 km in the Lamat, Senowo III, and Sat drainages. As a result of these events and observations the alert level was raised to IV (*Awas Merapi*) at 0438, for the Sat, Senowo, Lamat, Blongkeng, Bebeng and Krasak drainages.

Activity continued to build with an eruption plume that varied in height to 2 km above the summit, while at about 0445–0455, nuées ardentes traveled as far as 5.5 km along the western drainages. The hot currents devastated some pine forests and farms, but did not reach village houses (Fig. 7). These were the most powerful events of the day. The alarm was turned


A
Lava 1992
Sketched by Sunarto
From Plawangan Observatory
February 15, 1993 ; 06.15 LT
Lava 1984
K. Babeng
K. Bedok
K. Boyong
K. Kuning
K. Gendol
Source of avalanche
Direction of glowing avalanche
Location of glowing avalanche jumping down into Boyong River and Bedog River
Kali (River)
B
1992/1993
1994
Sketched by : Sunarto
From : Plawangan Observatory
March 29. 1994
K. Babeng
K. Bedok
K. Boyong
K. Kuning
K. Gendol
Source of avalanche
Direction of glowing avalanche
K Kali (River)

on at 0458. By the end of the episode, 36 nuées had been generated, with most running to the west. Due to the time of day (no workers had yet gone to their farms), the heightened alert, and the long-term prohibition on inhabitation of this sector, no lives were lost in this eruption.

On noon 12 July the alert level was lowered to III (*Siaga Merapi*), and this was maintained to a distance of 8 km from the summit in the west and southwest sectors. On 17 July tiltmeter T4, having been removed from Klatakan on 10 July and repaired, was installed near the summit; but unfortunately fog and fumarole plumes prevented observations of the dome. Two days later on 19 July, after a week of generally rising gugurans but declining MPs, a series of 25 nuées ardentes were generated, with maximum runout of about 5.5 km toward the Lamat and Senowo drainages. Rockfalls continued and many were incandescent, with runouts <1 km. Plumes associated with the nuées rose as much as 6 km and spread ash to Muntilan.

The nuées were accompanied by a burst of MP activity, with 347 MP events occurring between 0600 and 1313. The first nuée occurred at 0629, traveling 5 km toward the Lamat. Tremor was reported between 1325 and 1503, punctuated by five nuées with runout between 2 and 5 km (4 episodes of tremor were recorded in July, usually during vigorous activity). At 1330, VSI requested sand-and-gravel workers in drainages in the western sector to cease operations. An eruption was recorded at 15:01, accompanied by nuées to 5.5 km and an eruption plume 6 km above the summit, with a few mm of ash falling in Muntilan. Nuées continued until 1800. Overall in this episode, 16 VTBs, 399 MPs, and 119 gugurans occurred. Over the next week seismicity declined, but the level III alert was maintained until noon 3 August. No deaths were reported in these events. The total amount of pyroclastic material deposited in July was estimated at $8.8 \times 10^6\ m^3$. This relatively large volume suggested the possibility of a partly explosive process rather than the simple gravity collapse of November 1994, when far less pyroclastic material was produced (SEAN, v.23(8)).

5. Discussion of eruption precursors and the timing of mitigation measures

No dramatic increases in precursory phenomena were recorded during 1994 or 1995. Since no significant eruptive activity occurred in 1995, this is not surprising. However the 1994 event caused more casualties than any eruption since 1954, so the lack of any short-term precursor—resulting in an insufficient time for officials to react to the alert—requires explanation. We view the lack of precursors in 1994 as consistent with the generation of these nuées ardentes by purely gravitational instability. This instability had been created gradually by slow extrusion of lava high on the southwest slope, with the lava volume increasing without steady deterioration by small rockfalls. Thus the ratio of average shear resistance to shear forces tending to drive motion gradually built to the critical level. The eruption was not triggered by a rapid period of dome growth accompanied by gas-rich lava.

The casualties in 1994 reflected the lack of short-term precursors, but also the lack of full and clear appreciation of the hazard to the south flank (Sukhyar, 1995). The villagers on this flank had not been affected by nuées ardentes for several generations, and they were not prepared even though rockfall runout in this direction had been mentioned (although probably insufficiently emphasized) in the Berita Merapi (Merapi News) distributed to local governments. The post observers at Plawangan had made photographs or sketches of rockfalls in this direction, although with very limited runout (< 2 km), since 1993 (Fig. 16). This southern direction was unusual, inasmuch as previously the clear pyroclastic runout path had been exclusively to the southwest, but the direction of the chute below the

Fig. 16. (A). Sketch by an observer on 15 February 1993 at Plawangan post on the south flank. Rockfalls are shown jumping the channel rim at two locations indicated by a star, entering the drainages of the Bedok and Boyong rivers. Similar observations were made throughout most of 1994. These rockfalls were minor and did not travel far. However the large nuées ardentes of 22 November 1994 followed a similar path, causing a large number of casualties at Turgo and Kaliurang where both the population and hazard managers were largely taken by surprise. (B). Sketch from the same position on 29 March 1994. Note changes at summit from extrusion of 1994 lava. Some rockfalls during this period entered the Bedok and Boyong headwater areas.

dome, and the accumulating lava debris against the south runout channel, had made it possible for some flows to surmount this channel-wall obstacle and to head southward into populated regions (Fig. 2A). Indeed the direction was considered so unusual that some experienced foreign scientists very familiar with Merapi found it difficult to understand, even many months afterward, how the nuées could have moved southward. However, a glance at the runout geometry in Fig. 2A makes the issue clear. Thus by the time the highest level (IV) alert was given by MVO to the observation posts in 1994—a mere half-hour in advance of the *crucial* event—the message could not be communicated efficiently to the population at risk, who in any case were unprepared for the message.

One of the important lessons of this affair is, that appropriate attention must be given by scientists to the directions taken by small rockfalls as a vital clue to the movement directions of future major nuées ardente lobes. A second lesson is, that the implications of these observations must be reliably communicated with adequate lead time to public officials and civil defense, and the population at risk must be well-enough educated to the danger, and warned. However, irrespective of whether or not a given nuée ardente will actually follow these "rockfall-directions" depends on the initial travel paths of large masses of dome rock, and the manner in which the collapse evolves, and these aspects are difficult to reliably predict in advance. The uncertainty requires that a conservative approach be considered for hazard management, such as early warning before an outcome is assured. However, this approach is costly and may result in some so-called "false alarms." Both the population and officials need to be prepared for this outcome.

After 1994, some rockfalls had moved toward the Boyong river in 1996, 1997, and 1998 (Figs. 8 and 11). Although these rockfalls were recognized by VSI staff, only in 1996 was an early evacuation carried out in this sector, although no large event then occurred. In 1997 an evacuation was carried out, but only *after* the occurrence of a large event; this nuée in fact brought pyroclastic deposition into the critical sector but fortunately not quite far enough to cause casualties.

Notable short-term accelerations in tilt rate occurred prior to the major nuées ardentes episodes in 1996/1997 and 1998. In 1998 the tilt trend began to change in early June but showed dramatic changes in late June and early July. The increase in MP seismicity closely correlated with tilt, with rockfalls lagging by several days, but all three indicators showed anomalous behavior for a full week before the peak of eruptive activity on 8–11 July (Figs. 14 and 15).

For 1996/1997 we can divide the tilt record into three segments (Fig. 10), (1) a period from 1 July to about 2 December 1996 with steadily increasing tilt, (2) a period with tilt increasing distinctly at a faster rate, to 7 January 1997, and (3) a short period to 14 January with tilt increasing at an even faster rate. Large nuées ardentes occurred on 14 January, in association with a VTB swarm, and a vulcanian explosion followed on 17 January. A buildup of MP seismicity accompanied accelerated tilt after 7 January (Fig. 12). An earlier, more-pronounced buildup of MP energy had preceded a crisis at the end of October, but this phase lacked any comparable change in tilt behavior (Fig. 10).

In 1997 and probably in 1998, the eruptions were preceded by a period of increasing dome growth with (relatively) gas-rich magma, and the large precursory tilt and MP activity in these events is consistent with a larger pressure gradient and enhanced lava flux. The onset of a short-term, precursory acceleration in tilt on 11 January was preceded a few days earlier by the onset of MP activity (Fig. 12). This suggests that the pressure buildup responsible for this latest tilt increase was preceded by an increase in rate of effusion that is presumed to be associated with MP activity. However, an anomalous increase in tilt had also been noted since December, without associated MP activity (Fig. 10). In 1998 both phenomena appeared to have begun to increase at about the same time, on 30 June (Figs. 14 and 15).

Over the years of observation a successively faster rate of outward tilt had been observed on the summit tiltmeter T3. Precursory to modest nuées ardentes episodes circa 1993, inflationary tilts were recorded on the order of 30–40 μrad/day (Young et al, 1994). In 1997, we observed tilt on the order of 200 μrad/day, and in 1998 about 5000 μrad/day (Figs. 10 and 14). The increase from 1993 to 1997 may reflect the intensity of pressurization. However, the enormous magnitude in 1998 reflects a concentrated deformation of loosened edifice rock mass at the tilt station, just as this part of the edifice was about to collapse.

The clear buildup of precursory deformation and seismicity contributed to the raising of alert levels before the large nuées ardentes of 1997 and 1998, and this, together with the long-term prohibition on settlements and the time of day, contributed to the lack of casualties. But it was also simply fortunate that the large nuées did not develop far-travelling tongues in the populated southern drainages. The timing of the assignment of alert level IV (*Awas Merapi*), indicating evacuation, was not early enough for useful warnings in 1997 and 1998. Rather, the alerts coincided more or less with the timing of the major nuées ardentes, rather than preceding them by any significant lead-time interval that would be necessary for implementation of evacuation in any area with a significant population. Likewise the nuées of 19 July 1998 occurred when a level III alert was in force.

The alert that had been issued in the October 1996 crisis was timely for the Boyong drainage, although no major nuées ardentes were generated afterward. A question that arises is whether this "apparently needless" (although fully justifiable) evacuation may have influenced the timing of the alerts issued in 1997 and 1998. The question is difficult to answer, but in Subandrio's opinion (written communication), the resistance of sediment-collection workers in the Bebeng and Krasak riverbeds to evacuate in 1997, when *Awas* had been announced, had nothing to do with the 1996 experience. Rather, it reflected the economic reason of loss of revenue, and also their poor understanding of the danger of the "*awan panas*" (nuée ardente). "*They thought that the awan panas was like a lahar,"* and indeed the common people did not know the terms *lahar*, *awan panas*, lava etc. Also, the "sand"-workers were not only local residents, but also truck drivers, food sellers etc from other regions or villages, unfamiliar with the volcano hazards.

Apparently, the time between an *Awas* alert and initiation of evacuation by SATORLAK is short, because when the alert status is raised to *Siaga*, the key people (SATGAS) of SATORLAK go to the evacuation site. No discussions are necessary when the *Awas* is given, as a standard procedure is followed with military command style (Subandrio, written communication). This emphasizes the importance of the timing of the *Siaga* alerts.

The discussion above highlights some practical problems commonly faced by authorities and advisor scientists when dealing with the extremely difficult philosophical, political, and social problem of proper timing (J. Lockwood, written communication; Voight, 1996). Should authorities give the "earliest possible" evacuation warnings (when they don't *really* know with certainty what will happen)—or should they wait until they are more certain (and likely too late)? This question, of course, frames the extremes of the spectrum, and the appropriate answer will vary from country to country and from time to time, and be dependent strongly upon economic and cultural issues. For Merapi, some workers at MVO think it advisable to announce *Siaga* status as early as possible in order to aid the readiness of both the people and SATORLAK. Further, the need for education of the local populace through schools, and by cooperation of local government and non-governmental organizations, is recognized. Some education measures are now carried out, and occasional evacuation exercises are held.

But in the end, it all boils down to when the *Awas* alerts are actually given. This much seems clear: if relocations, evacuation costs and "false alarms" are all not acceptable, then the resulting consequence is enhanced risk of casualties. If a series of false evacuations is considered unaffordable, as may be the case in many countries, then the choice comes down to relocation, or bearing the high risk of casualties in future events.

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Appendix A. Inferences of pressure distribution from tilt data

Data from five tilt stations operating during the

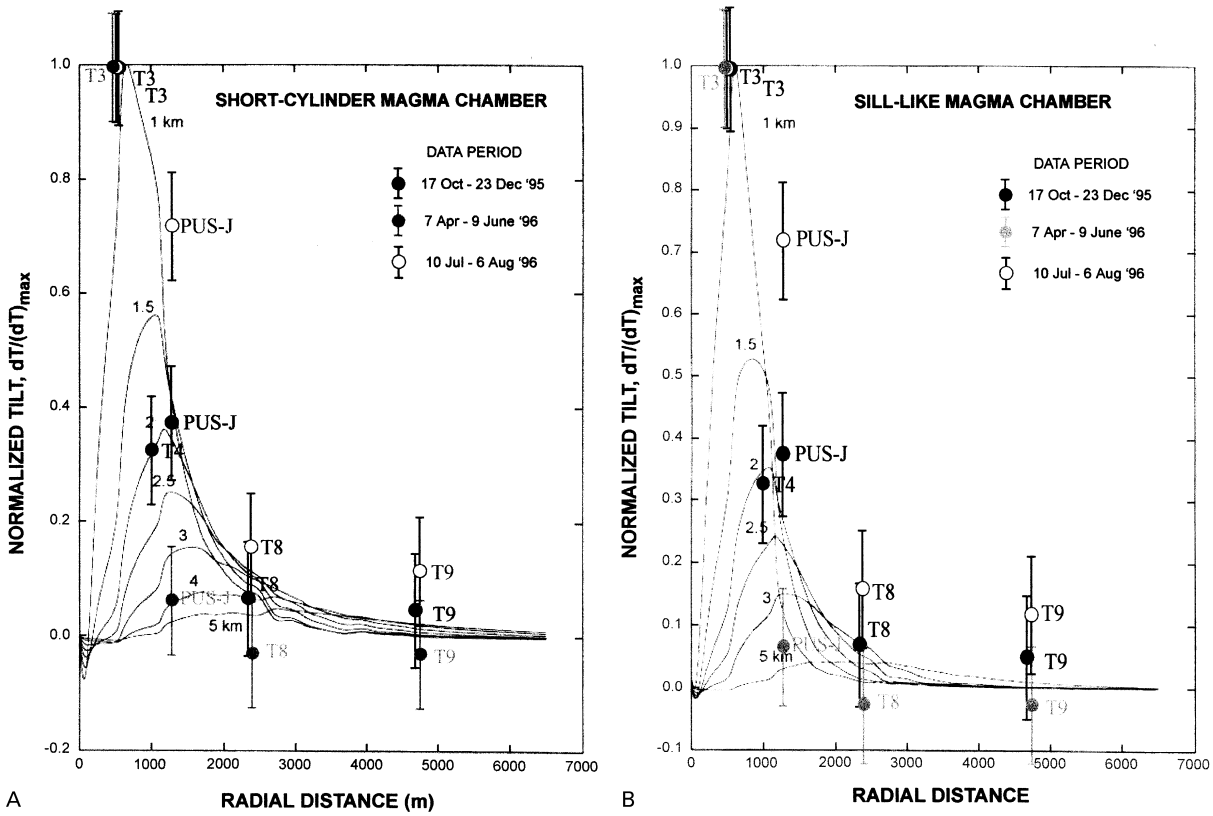

Fig. 17. Normalized tilt against radial horizontal distance from conduit. Data points for three time periods in Fig. 9, as illustrated. Error bars correspond to an arbitrary 10% deviation from maximum tilt change. Theoretical curves from axially-symmetric finite-difference models using south flank topography. (A). Pressurized cylindrical magma chamber, diameter equal to height. (B). Pressurized sill-like chamber. Data suggest influence of a shallow pressure source but are inconsistent on the shape.

period 17 October 1995 to 6 August 1996 (Fig. 9) are plotted on a plot of normalized radial tilt against radial distance from the summit, in Fig. 17. The data are compared to theoretical deformation curves based on isotropic elastic behavior of the Merapi cone (assuming axial symmetry with geometry based on south-flank elevation data) subjected to interior uniformly pressurized zones of different shape and depth. The data show no overall consistency with respect to the theoretical curves. The 1995 data are most consistent with the curve for an equant-shaped chamber, height equal to diameter, located about 1 km beneath the summit (Fig. 17A). The July–August 1996 data also fit closest to this model, although no curve is actually well-fit. The April–June 1996 data seem more consistent with a sill-like chamber (Fig. 17B). In all cases the peak tilt occurs at the summit station at a radial distance that is consistent with a shallow pressure source. For a deeper source, the theoretical tilt should peak at a greater radial distance (Fig. 17), but this is not reflected by the data. These preliminary results are qualitatively not inconsistent with previous ideas of a small shallow magma chamber in Merapi, based on seismic and gravity monitoring (Ratdomopurbo and Poupinet, 2000 – this volume; Jousset et al., 2000 – this volume). Nevertheless we view these results as very tentative because modeling is simple, axial symmetry is assumed rather than the actual three-dimensional shape, only normal stresses are introduced in the model, and shear stresses associated with conduit flow are neglected. Beauducel and Cornet (1999) have proposed a deep chamber, at ~9 km depth, based on regional deformations. Deep and shallow pressure sources are not mutually exclusive concepts, and indeed the anomalous large tilts recorded at distant stations supports the notion that the data could represent the cumulative influence of deep-seated pressurization superimposed upon shallow conduit pressurization. We suspect that magma pressurization inside Merapi may be complex, and that the surface deformation may indeed result from the superposition of multiple pressurization sources (Sajiman, oral communication). Viscosity is likely highest at shallow levels, suggesting that shear tractions also need to be included in deformation models.

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