News feature

Merapi (Java, Indonesia): anatomy of a killer volcano

Merapi is Indonesia's most dangerous volcano with a history of deadly eruptions. Over the past two centuries, the volcanic activity has been dominated by prolonged periods of lava dome growth and intermittent gravitational or explosive dome failures to produce pyroclastic flows every few years. Explosive eruptions, such as in 2010, have occurred occasionally during this period, but were more common in pre-historical time, during which a collapse of the western sector of the volcano occurred at least once. Variations in magma supply from depth, magma ascent rates and the degassing behaviour during ascent are thought to be important factors that control whether Merapi erupts effusively or explosively. A combination of sub-surface processes operating at relatively shallow depth inside the volcano, including complex conduit processes and the release of carbon dioxide into the magmatic system through assimilation of carbonate crustal rocks, may result in unpredictable explosive behaviour during periods of dome growth. Pyroclastic flows generated by gravitational or explosive lava dome collapses and subsequent lahars remain the most likely immediate hazards near the volcano, although the possibility of more violent eruptions that affect areas farther away from the volcano cannot be fully discounted. In order to improve hazard assessment during future volcanic crises at Merapi, we consider it crucial to improve our understanding of the processes operating in the volcano's plumbing system and their surface manifestations, to generate accurate hazard zonation maps that make use of numerical mass flow models on a realistic digital terrain model, and to utilize probabilistic information on eruption recurrence and inundation areas.

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The Indonesian archipelago is dotted with volcanoes. The Smithsonian Global Volcanism Program database currently lists 145 Holocene (i.e. active) volcanoes, more than half of which have erupted since human records began. Most of these volcanoes belong to the Sunda arc, a volcanic island chain formed by the subduction of the Indian Ocean lithosphere beneath the Eurasian plate that underlies Indonesia, stretching eastwards from Sumatra to Java and the Lesser Sunda Islands (Fig. 1).

Merapi is a majestic volcanic peak, almost 3000 metres high, located in the heart of the Sunda arc in Central Java. When it erupts, it is the most dangerous volcano in Indonesia and, in the past, it has done so every few years. On a clear day, Merapi, and its equally impressive neighbour Merbabu, can be seen in the far distance from the city of Yogyakarta that lies some 30 km to the south. A white plume from fumarolic activity at the summit is often easily visible, but only a closer look reveals the culprit behind Merapi's frequent eruptions (Fig. 2). Typically, a dome of viscous basaltic andesite lava grows on top of the steep-sided cone, which, when big enough, may collapse to generate pyroclastic flows, a deadly volcanic phenomenon. These flows are mixtures of lava dome fragments up to several metres in size, smaller

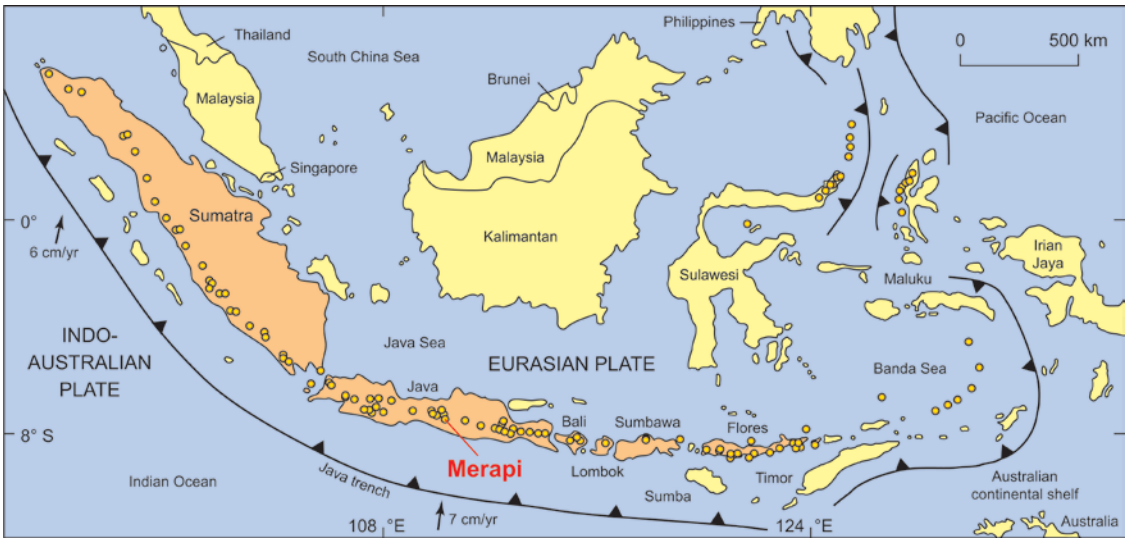

Fig. 1. Map of the Indonesian archipelago and the location of Merapi in Central Java. The Sunda arc (islands with active volcanoes are highlighted in orange) is the part of the Indonesian subduction zone system that stretches from Sumatra in the west to the Lesser Sunda Islands in the east.

volcanic particles (ash) and hot gases that may travel down the flanks of the volcano at velocities of more than 100 km/h and distances of several kilometres, well into inhabited areas. This eruption style has been so typical of Merapi that pyroclastic flows generated in such a way are often referred to in the literature as 'Merapi-type' nuées ardentes (i.e. 'Merapi-type' glowing clouds). When Merapi re-awakened in 2010 after four years of quiescence, its eruptive behaviour was dramatically different. In this article, we evaluate the catastrophic 2010 events in the light of what is known about the volcano's past activity, explore what its future may hold and consider the volcanic hazards it continues to pose to the surrounding population.

Fig. 2. Merapi and its summit lava dome as seen from the Boyong valley to the south (photo taken in 1999).

The eruptive events in October and November 2010

On 26 October 2010, Merapi erupted after nearly two months of enhanced levels of seismicity and ground deformation, which ended a period of low-level activity since the preceding eruptive episode in 2006. Two days before the eruption, a sharp increase in the number of volcanic earthquakes and the rate of summit deformation was observed, which prompted the evacuation of several villages within a 10 km radius of the summit. In the events on 26 October, at least 34 people were killed in the village of Kinarejo, some 5 km from the summit, when a series of pyroclastic flows swept down the southern flank of the volcano. The exact generation mechanisms and nature of these flows remained speculative, as visual observations were often difficult due to inclement weather or activity at night. Reports of booming noises and explosions suggested that there migt have been a collapse of near-vertical eruption fountains (rather than a lava dome) or, even, more horizontally directed explosions. However, it appears that the destruction of Kinarejo was mostly due to ash-cloud surges that detached from flows channelled into the Gendol valley (Fig. 3). In the days that followed, the activity remained at a high level. Glowing avalanches with runouts of up to 12 km, presumably from a new lava dome that had started to fill the newly formed summit depression (Gendol breach), were produced, and continued large explosions generated a 7 km-high eruption column and ash fall tens of kilometres away from the volcano

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Fig. 3. The structure of the Merapi volcanic complex: New Merapi (left) and the remnants of Old Merapi (right) as seen from the south. The Gendol valley filled with pyroclastic flow deposits from the 2006 eruption is in the foreground (photo taken in 2007).

on 4 November 2010. These events led to further extensions of the 'safety zone', to evacuations from several more communities within a 20 km radius and to the temporary closure of Yogyakarta airport. On 5 November, an unusually large eruption generated pyroclastic flows that were channelled for 15 km along the Gendol valley on Merapi's south flank. Associated ash-cloud surges swept through villages outside the valley, destroying everything in their path and causing hundreds of fatalities (as reported in *Geology Today*, 2011, v.27, n.1). During November, the activity continued with lower intensity, generating rock falls, pyroclastic flows and occasional volcanic mudflows (lahars). By early December, the death toll had risen to 322 people, making this eruption the greatest volcanic disaster at Merapi in 80 years. On 4 December 2010, was the alert level lowered to 3 (on a scale of 1–4).

Merapi's fiery past: a short account of a long story

Merapi, which literally means 'Fire Mountain' in Javanese, is a complex volcanic edifice which, as hitherto unpublished radiometric age determinations by the authors suggest, dates back to at least 170 000 BP. The most recent and active part of the volcanic complex, a young composite cone commonly referred to as New Merapi, is merely a few thousand years old. It has formed on top of the remnants of an older volcanic edifice (Old Merapi), which was destroyed by one or, possibly several, lateral collapses of its western flank along a major fault zone, known as the Kukusan fault. This replaced its summit with a horseshoe-shaped crater and left an avalanche caldera rim high on the northern and eastern flanks (Fig. 3). The observational record of eruptions at Merapi goes back to the mid-1500s, but only becomes more complete in the second half of the eighteenth century, with almost continuous activity until today (Fig. 4). During this period, the eruptive activity has been dominated by relatively small, dome-forming eruptions, characterized by prolonged periods of slow lava dome growth and intermittent dome failures, which were only occasionally interrupted by more explosive eruptions. A volcanic explosivity index (VEI) of 2 or 3 (on an open-ended scale with the largest volcanoes in history given a VEI of 8) has been assigned to most of Merapi's historical eruptions. Associated pyroclastic flows affected primarily the western slopes to distances of typically less than 10 km from the volcano. Pyroclastic flows from the most recent eruptions have followed this general pattern, but notably filled the valleys of the Boyong (1994) and the Gendol (2006, 2010) rivers on the heavily populated south flank of Merapi up to 15 km from the summit, causing the destruction of inhabited areas and fatalities. Prior to 2010, pyroclastic flows with runouts greater than 10 km in historical time occurred only during Merapi's worst volcanic disaster in 1930, where 36 villages were wiped out or partly destroyed and 1369 people were killed (Fig. 5).

Eruptions further back in time, inferred from the description, interpretation and dating of past eruptive deposits (Fig. 6), appear to have been nearly as frequent as during historical time, at least over the past ~ 2000 years, beyond which the radiocarbon record

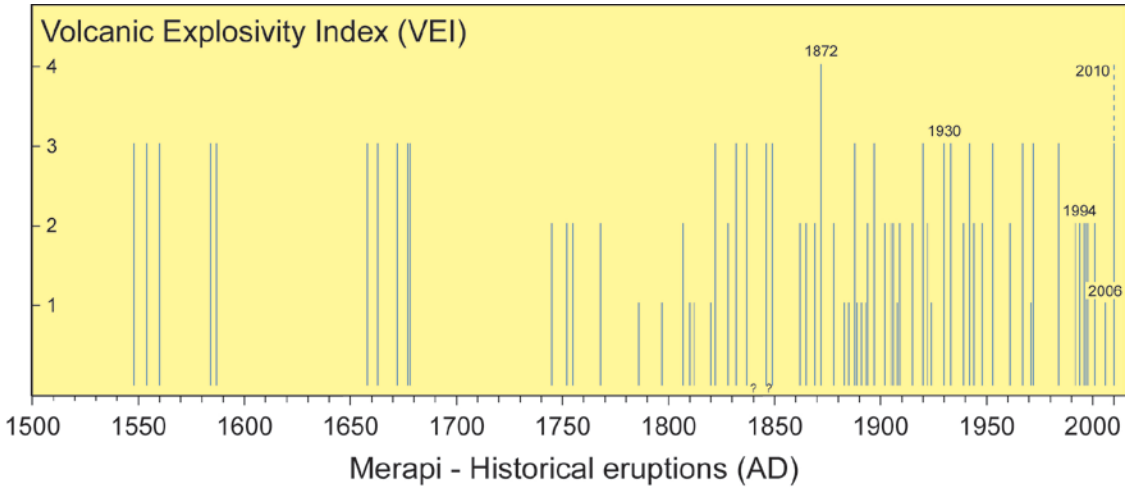

Fig. 4. Merapi's historical eruption record. Notable volcanic disasters that caused fatalities are indicated by the year in which they occurred.

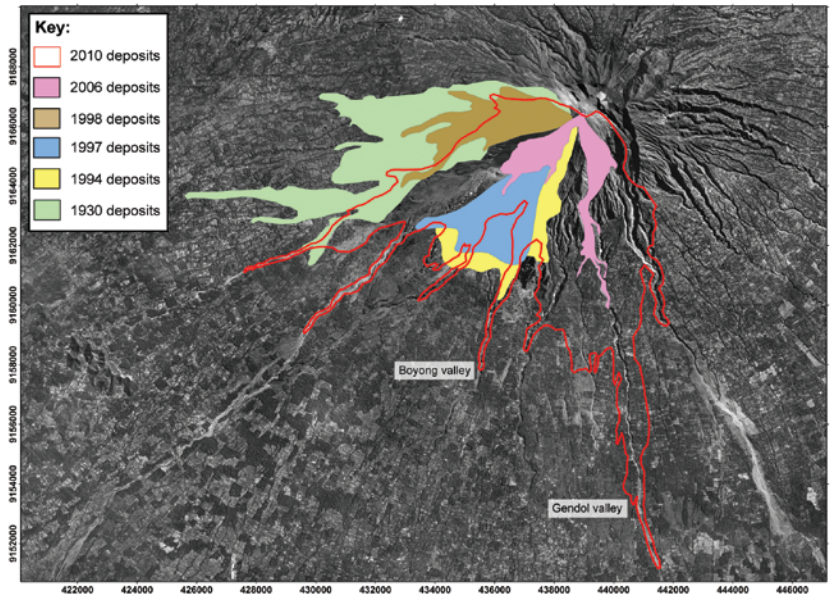

Fig. 5. Map of the pyroclastic flow deposits from Merapi's most recent eruptions since 1994. The area affected by the most devastating historical eruption in 1930 is shown for comparison. The map coordinates are in UTM metres.

of Merapi, which currently extends back to 11 792 ± 90 BP, becomes less complete. The Holocene stratigraphical record reveals that fountain-collapse pyroclastic flows, which have been relatively rare during the more recent activity, are a common phenomenon at Merapi. Their deposits are characteristically rich in pumiceous clasts or breadcrust bombs. One of the most prominent examples of this type of flow is a young, most probably historical pyroclastic flow deposit rich in breadcrust bombs that can be traced over large areas on Merapi's south flank (Fig. 7a). Additionally, widespread pumiceous fallout deposits testify to the occurrence of moderate to large explosive (sub-Plinian) eruptions (VEI 3–4) during the mid to late Holocene (Fig. 7b). It is noteworthy that VEI 4 eruptions, as identified in the stratigraphical record, are an order of magnitude larger than any recorded historical Merapi eruption, except for the 1872 and, possibly, the 2010 events.

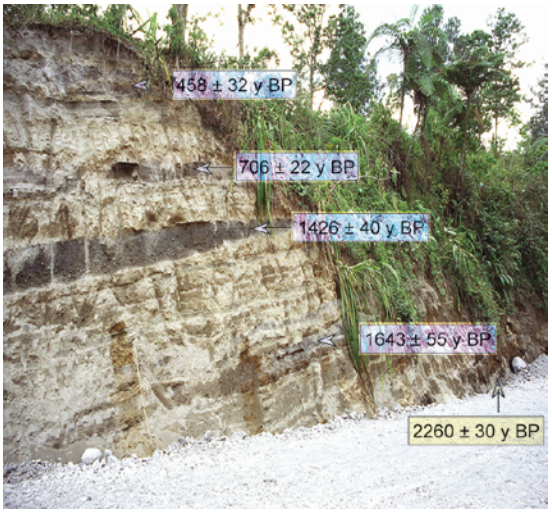

Fig. 6. Pyroclastic deposits from past eruptions exposed in a roadcut at Jurangjero on Merapi's southwest flank. The sequence, dated by the radiocarbon method, records more than 2000 years of intermittent explosive eruptions.

Clues in the rocks

The volcanic rocks and ash produced in a volcanic eruption preserve a record of the pre-eruptive, subsurface processes that operate inside the volcano. The story written in the rocks from Merapi's past activity indicates that the chemical compositions of the erupted magmas have been relatively uniform regardless of whether the eruptions were effusive or explosive. Analysis of melt inclusions, tiny 'blobs' of molten rock that are trapped in crystals as they grow within the magmatic system of the volcano, have shown that the Merapi magmas are rich enough in water to stabilize amphibole, a water-bearing mineral that breaks down within days to weeks during slow rise of magma towards the surface (Fig. 8a). In the past, it appears that effusive (dome-forming) eruptions were generally associated with the extrusion of largely degassed magma, where gas could escape from the magma before reaching the surface during slow ascent or temporary storage at shallow depth within the crust. By contrast, amphiboles in rocks from explosive eruptions (Fig. 8b) suggest that they were fed by volatile-rich and, in some cases, also by more primitive magma that rose rapidly from a deeper reservoir without significant gas leakage from

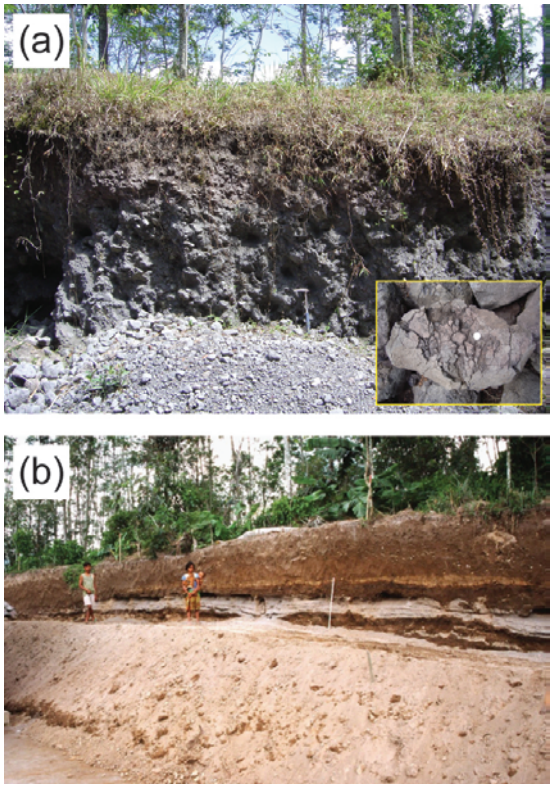

Fig. 7. a. Young explosion-type pyroclastic flow deposit rich in breadcrust bombs on Merapi's south flank. **b.** Pumiceous fallout deposit (white layer) from a late Holocene (~ 450-year-old) sub-Plinian eruption in an exposure in Kaliadem on Merapi's south flank.

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the magma before it reached the surface. Thus, variations in magma supply from depth, magma ascent rates and the degassing behaviour during ascent are thought to exert prime controls on the eruptive behaviour of Merapi. However, this is only part of the story. There are many processes acting on the magma during ascent, particularly at relatively shallow levels within the volcano's plumbing system, that may lead to changes from effusive to explosive behaviour (and vice versa) and, ultimately, determine the dynamics of Merapi-style volcanism. For example, the crystals in the erupting magmas often preserve a record of multiple magma mixing events, emphasizing the importance of magma replenishment processes during temporary magma storage at various depths within the crust. Magma ascent at shallow depth inevitably results in decompression-induced crystallization and vesiculation which, together with complex conduit processes, affect both magma and eruption dynamics. Calc-silicate xenoliths brought up by the Merapi magmas (Fig. 8c) indicate that assimilation of carbonate rocks from the sub-volcanic crustal basement is an important process at this volcano, with potential implications for relatively abrupt shifts to explosive behaviour during dome-forming eruptions through a late crustal carbon dioxide input into the magmatic system.

Possible future eruptions

If Merapi does erupt again, will it start with relatively benign growth of a new lava dome or will the onset be marked by a sudden explosive event like in 2010? Will the next eruption be on an even larger scale, similar to some of the eruptions in the geological record? Is there a risk of a large flank collapse, as has happened at least once in the history of Merapi? Prior to the onset of volcanic activity, there will be precursory signs, such as an increase in the number and intensity of local earthquakes and detectable ground deformation, which, once they appear, can be used to anticipate several days to weeks in advance when the next eruption is likely to occur. However, the catastrophic events in 2010 have shown that the magnitude and the course of Merapi's eruptions may take are far from being predictable. Similarly, it has become clear that the more common and perhaps less hazardous dome-forming eruptions may be interrupted at relatively short notice by larger explosive eruption phases. Thus, the challenge scientists face in anticipating the volcano's future behaviour is to unravel the driving forces behind Merapi's unusual explosive activity and the critical changes that may lead to a change in eruptive style. Merapi's past and present eruptions may well hold the key to its future behaviour. As such, the study of these eruptions is crucial to constrain the pre-eruptive processes and timescales of magma storage and ascent operating inside the volcano system. Important clues may be gleaned from more recent, well monitored eruptive episodes, where the pre-eruptive, sub-surface processes preserved in the rocks can be linked to their surface manifestations as recorded in the geophysical monitoring data of the eruption. An improved understanding of the physical and chemical processes that lead to magma ascent and eruption will allow more reliable interpretations of volcano monitoring data and will ultimately lead to better monitoring strategies and more accurate short-term hazard assessments during future unrest.

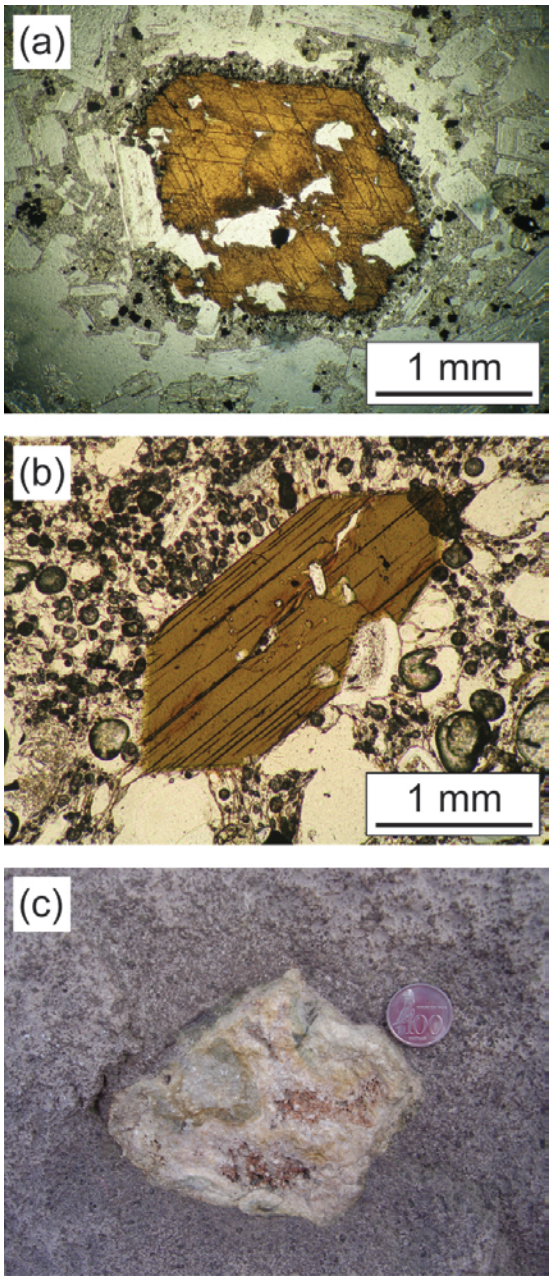

Fig. 8. **a.** Amphibole with typical breakdown rim of pyroxene, plagioclase and magnetite in a lava dome sample from the 1994 eruption. **b.** Fresh amphibole in a pumiceous clast from a late Holocene explosive (sub-Plinian) eruption. **c.** Calc-silicate xenolith in the 2006 pyroclastic flow deposits.

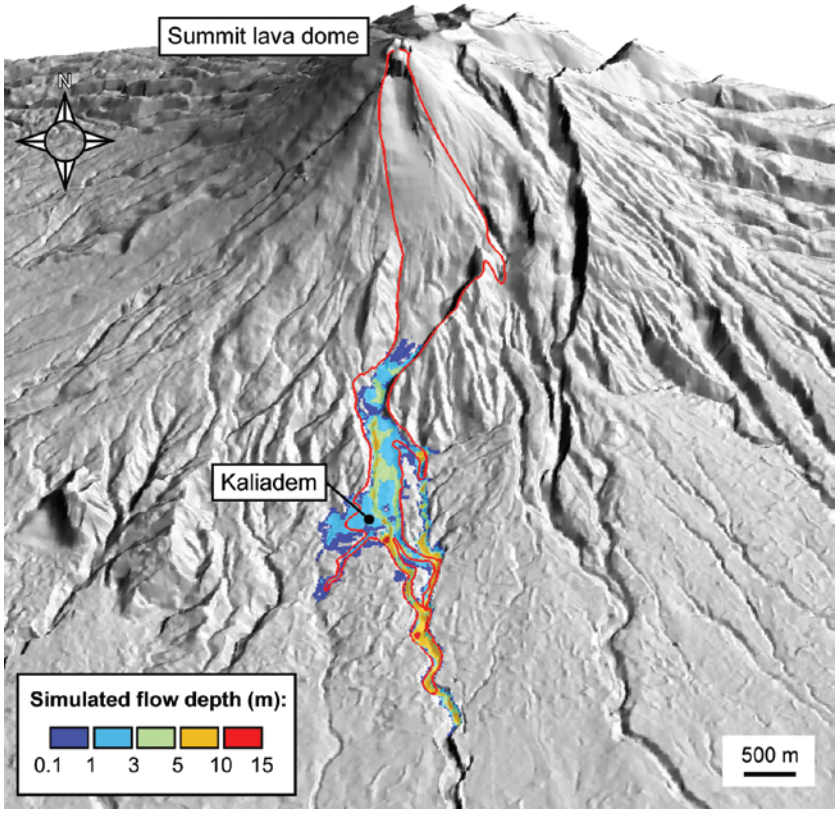

Fig. 9. Numerical simulation of a pyroclastic flow channelled along the Gendol valley on Merapi's south flank as observed in 2006. The simulation was performed using the Titan2D mass flow code developed at the State University of New York at Buffalo. The red outline is the mapped extent of the June 2006 pyroclastic flow deposits in the field. The village of Kaliadem was partly destroyed and two people were killed during the eruption. The same area has been affected by pyroclastic flows in 2010.

Living with Merapi: continuing volcanic hazards

The continuing eruptive activity at Merapi poses a permanent threat to the over 1 million inhabitants in the surrounding area for the foreseeable future. Devastating pyroclastic flows generated by gravitational or explosive lava dome failures and subsequent lahars remain the most likely hazards near the volcano. However, given Merapi's more powerful eruptions in the past and short-term alternations between effusive and explosive phases as observed in 2010, the possibility of violent eruptions that affect areas farther away from the volcano in the future cannot be discounted. Integration of Merapi's past eruption record into the existing volcanic hazard map, which is primarily based on the small dome-forming eruptions of the twentieth century, is considered crucial for longer-term hazard assessment and reduction of volcanic risk. Accurate hazard zonation maps, prepared using numerical mass flow models on a continually updated digital terrain model and, where appropriate, probabilistic information on eruption recurrence and inundation areas, are vital to better assess potential future hazards (Fig. 9). It is essential that these maps are regularly renewed as new data and modelling results become available in order for them to serve as critical inputs for emergency plans, preparedness activities and crisis management. Hazardous volcanic activity will continue to occur at Merapi and, because of rising population pressure, risks to life and property through exposure to volcanic hazards will continue to increase. Since the mid 1990s, intensive volcano monitoring programmes, carried out or coordinated by the Merapi Volcano Observatory, have greatly improved the capability of scientists to detect signs of geological unrest at Merapi, monitor its activity and, that way, provide sound advice to authorities, decision makers and the population during volcanic crises. It is due to this, that in 2010 a volcanic disaster similar to or even greater than that in 1930 has been prevented.

Suggestions for further reading

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