

# Volcanic threat in developing countries of the Asia–Pacific region: probabilistic hazard assessment, population risks, and information gaps

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**Abstract** The importance of disaster reduction has gained increased awareness within the international development community and thereby highlighted a need for a preliminary assessment of natural hazard risk in developing countries of the Asia–Pacific, including that for volcanic eruption. In this paper, we present a key component of such an assessment, which involved qualifying the frequency and potential consequences of large—Volcanic Explosivity Index of four or more—volcanic eruptions. The frequencies of large eruptions from volcanoes grouped by region were determined from frequency–magnitude plots using data provided by the Smithsonian Institution’s Global Volcanism Program. However, calculated frequencies represent only minimum values due to an incomplete eruption record. Unfortunately, limited data precluded the calculation of eruption frequencies for the Solomon Islands, Fiji and Samoa. A first-order analysis of the populations potentially impacted by large volcanic eruptions suggest that (1) volcanic disasters affecting populations of >100,000 can be expected at least every decade in Indonesia and once every few decades in the Philippines and (2) a volcanic disaster impacting >1% of the population can be expected twice a century in Vanuatu, twice a millennium for Indonesia and the Philippines, and around every millennium in Papua New Guinea and Tonga.

**Keywords** Probabilistic volcanic eruption frequency · Volcanic risk · Landscan · Indonesia · Papua New Guinea · Philippines · Vanuatu · Tonga

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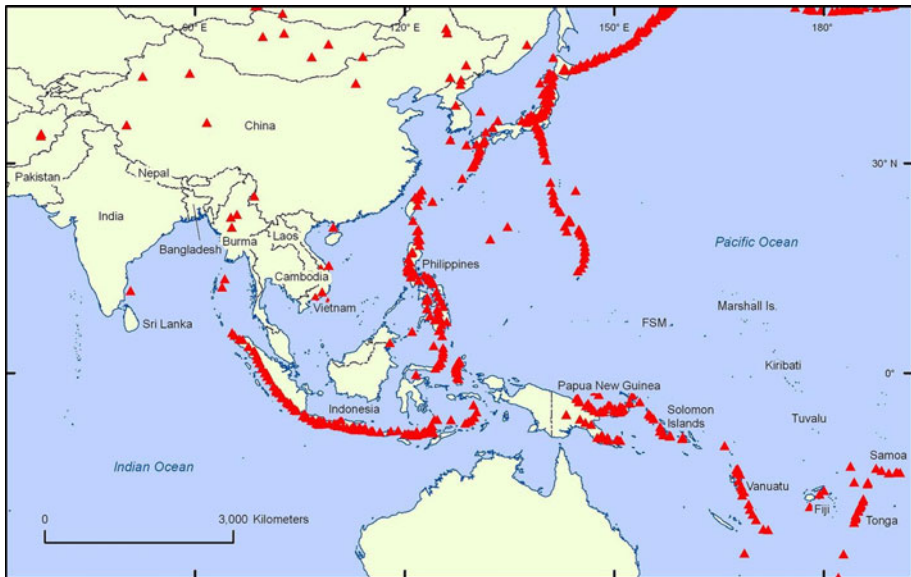
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## 1 Introduction

The management of natural hazards is a fundamental issue for sustainable economic and social development as the number and seriousness of disasters has been clearly demonstrated to affect developing countries disproportionately. More than 90% of natural hazard deaths and 98% of people affected by natural hazards in 1991–2005 were from developing countries (EM-DAT: The International Emergency Events Database). These disasters significantly compromise development progress and reduce the effectiveness of development investments. Disasters may halt or slow progress towards the achievement of the United Nations Millennium Development Goals (MDGs), and progress on MDG1 in particular—halving poverty and hunger by 2015—may be halted or reversed during a natural disaster. Second, disasters require a significant relief and humanitarian response from aid agencies, particularly relatively infrequent, high-magnitude disasters such as the 2004 Indian Ocean Tsunami.

Geoscience Australia recently undertook a first-order natural hazard risk assessment across selected countries of the Asia–Pacific region for the Australian Agency for International Development (AusAID). Countries targeted in this study are highlighted in Fig. 1. The objective was to provide a better understanding of disaster risks across the AusAID portfolio and to support AusAID to better target disaster risk reduction and humanitarian response activities. This study sought to identify the characteristics, approximate frequency, location, and potential consequences of rapid-onset natural hazards, including earthquakes, tsunamis, landslides, floods, cyclones, floods, wildfires, and volcanic eruptions.

Here, we outline the methodology and results from the volcanic eruption hazard component of the study which focused on Indonesia, the Philippines, Papua New Guinea,



**Fig. 1** Countries in the Asia–Pacific region targeted in the multi-hazard risk assessment for AusAID. The locations of Holocene volcanoes from the Smithsonian Institute’s Global Volcanism Program are shown as red triangles

Vanuatu, Tonga, Solomon Islands, Fiji and Samoa. The risk from volcanic eruptions in the Asia–Pacific region is aptly described by the following quote from Simkin (1993): ‘The most dangerous situation of all is that of a large, unexpected explosive eruption from a long-dormant volcano in a densely populated area’. Our analysis indicates that approximately 200 million people in Asia–Pacific developing countries live within 50 km of a volcano believed to have been active in the last 10,000 years, and of these, 90% live near a volcano that has not been active in the last 50 years. Moreover, one-third of the largest volcanic eruptions worldwide since 1800 have taken place in the Asia–Pacific region, and in Indonesia alone, about 100,000 lives have been lost to volcanic disasters in the last 200 years. Closely following Indonesia in terms of the number of destructive and potentially destructive volcanoes are the Philippines, Papua New Guinea, Vanuatu, Tonga, and the Solomon Islands, Fiji and Samoa.

## 2 Assessing volcanic hazard

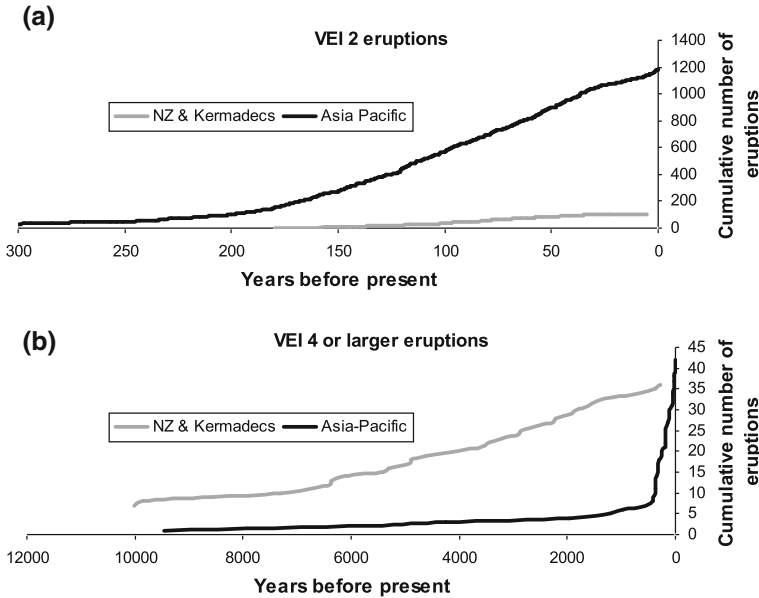
A complete history of volcanic eruptions can in principle be used to estimate how often eruptions of a given size may take place in the future. The potential of this approach was first revealed by a magnitude–frequency plot of worldwide eruptions in the last 10,000 years (Simkin and Siebert 1994). More recently, this type of probabilistic hazard assessment has been applied to individual volcanoes in New Zealand (Stirling and Wilson 2002) and Fiji (Cronin et al. 2001).

Magnitude–frequency plots were used in this study to determine the frequency of large eruptions in Indonesia, the Philippines, Papua New Guinea, Vanuatu, Tonga, Solomon Islands, Fiji and Samoa. ‘Large’ here means eruptions having a Volcanic Explosivity Index (VEI) 4 and larger (Newhall and Self 1982).<sup>1</sup> A file of volcanic eruptions in the region, provided by the Smithsonian Institution’s Global Volcanism Program (GVP), enabled the straightforward production of magnitude–frequency plots for each country and, to some extent, provinces within countries, in the region.

The GVP database is considered to be the most authoritative database of volcanic eruptions (Siebert and Simkin 2002). The GVP database only considers volcanoes that have erupted in the last 10,000 years. This captures almost all volcanoes likely to produce eruptions in the future and which are therefore ‘active’. However, a few volcanoes that were last active more than 10,000 years ago, and therefore are not included in the database, could possibly become active again. In addition to this limitation, two critical gaps exist in our knowledge of eruptions in the developing countries of the Asia–Pacific region. First, roughly half of the volcanoes in these countries are classified in the GVP database and are either volcanoes with no historical or dated eruptions or those for which geological evidence of Holocene eruptions is ambiguous. Geological evidence suggests that most of these volcanoes have been in eruption in the last 10,000 years, yet there has been insufficient investigation for the eruption chronologies to be determined. This means that it is not clear how frequently these volcanoes are active, and so they cannot be included in the frequency calculations. Yet, these ‘dormant’ volcanoes may be sites of future volcanic activity.

Second, there is a historical record of most moderate to large eruptions in developing countries in the Asia–Pacific region for the last 370 years, and particularly good records for the last 180 years, but this contrasts markedly with few or no records before 1630 A.D. The

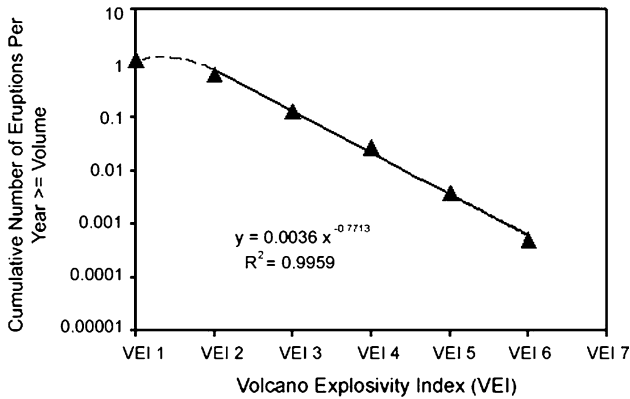
<sup>1</sup> A VEI 4 eruption has a bulk tephra volume of  $>0.1 \text{ km}^3$  (Newhall and Self 1982).



**Fig. 2** The large gap in eruption data in developing countries of the Asia–Pacific region is illustrated by comparing data from the Asia–Pacific developing countries with the data from New Zealand and the Kermadec Islands

short eruption record is an issue in determining the frequencies of large, yet relatively infrequent eruptions. A comparison of eruption records from the developing countries of the Asia–Pacific region and New Zealand (including the Kermadec Islands) illustrates the eruption incompleteness in Asia–Pacific developing countries (Fig. 2). The Asia–Pacific developing countries have an order of magnitude more VEI 2 eruptions than does New Zealand which is to be expected, given the high level of volcanic activity in countries such as Indonesia (Fig. 2a). In contrast, the developing countries appear to have a similar number of VEI 4 or larger eruptions as New Zealand in Fig. 2b. This apparent lack of VEI 4 eruptions in the developing countries is a result of the short available eruption record. Indeed, extension of the volcanic record in developing countries back to say 6,000 years would probably add a few hundred more VEI 4 or larger eruptions to the GVP database. The limitations associated with the eruption record in these developing countries means that the eruption frequencies reported here represent minimum values owing to substantial data gaps. Moreover, as the record for VEI 4 and larger eruptions is the most incomplete, the uncertainty in the frequency increases proportionally with VEI, an issue also explored in Huppert and Sparks (2006).

The first step in producing magnitude–frequency plots requires that the eruption record be assessed for completeness. Different sized eruptions have different time periods for which the record is relatively complete, and these periods may differ across the region. For example, large catastrophic eruptions may be remembered in local oral histories longer than smaller eruptions that had little impact. In addition, larger eruptions are better preserved in the geological record than are smaller ones. Consequently, a ‘complete’ record may be thousands of years for eruptions that were VEI 6 or larger, whereas a ‘complete’ record may only be 50 years for VEI 2 eruptions. A ‘complete’ record is represented on a



**Fig. 3** An example from the Philippines of a frequency–magnitude relationship used in this study to determine the frequency of different sized eruptions. *Note* tephra volume is roughly equivalent to VEI (Tephra Volume  $\approx 10^{(VEI-4)}$ ), for example, VEI 1 translates to 0.0001 km<sup>3</sup> and VEI 5 translates to 1 km<sup>3</sup>. A ‘roll-off’ or ‘curve shallowing’—marked by a *dashed line*—at the smallest eruptive volumes was found to be characteristic in most frequency–magnitude relationships. Thus, VEI 1 eruptions were generally not included in line-fit calculations [see Appendix 2 (Electronic supplementary material)]

graph by a relatively constant slope leading up to the present time (e.g., Fig. 2), assuming that eruption frequency is relatively constant through time. Only eruptions within the interval deemed to be ‘complete’ were used in frequency calculations—these intervals are documented in Appendix 1 (Electronic supplementary material).

The next step involves construction of magnitude–frequency plots in which eruption tephra volumes (relative to VEI) are plotted against the cumulative number of eruptions per year (Fig. 3). Almost all distributions show a ‘roll-off’ or ‘shallowing’ of the slope at the lowest eruption volumes (0.0001 km<sup>2</sup> or VEI 1) (Fig. 3), an observation also reported by Stirling and Wilson (2002). Fit of a power-law line, using least squares, to the magnitude–frequency distributions, enables the frequency of each eruption size to be determined. Here, eruption frequency is written as one in x years, where an eruption frequency of one in 400 years, for example, is equivalent to a probability of an eruption each year of 0.0025. Eruption frequencies for VEI 4, VEI 5, and VEI 6 eruptions in Indonesia, the Philippines, Papua New Guinea, Vanuatu, and Tonga are presented in Table 1. Note that the frequency of a ‘VEI 4’ eruption is actually the frequency of a VEI 4 and/or larger eruption because of the cumulative graph scale. The details of line fit for countries, and where feasible provinces, are available in Appendix 2 (Electronic supplementary material).

### 3 Frequency of large eruptions in selected Asia–Pacific developing countries

Indonesia has the most frequent VEI 4 or larger eruptions in the Asia–Pacific region and thus is considered to have the highest volcanic eruption hazard. The calculated frequency of large eruptions in Indonesia is one in 14 years (Table 1). Following closely are Papua New Guinea, Vanuatu, and the Philippines, where large eruptions have frequencies of one in 25, 40, and 50 years, respectively. A frequency of around one in 120 years was determined for Tonga. The eruption frequencies of the Solomon Islands, Fiji and Samoa, could not be determined owing to limited data (Table 1).

**Table 1** Frequency of large eruptions in targeted countries

Country	Frequency of VEI 4+ eruptions	Frequency of VEI 5+ eruptions	Frequency of VEI 6+ eruptions
Indonesia	1 in 14 years	1 in 99 years	1 in 679 years
Philippines	1 in 47 years	1 in 278 years	1 in 1,641 years
Papua New Guinea	1 in 25 years	1 in 149 years	1 in 8,98 years
Vanuatu	1 in 37 years	1 in 278 years	1 in 2,089 years
Tonga	1 in 118 years	1 in 556 years	1 in 2,621 years
Solomon Islands	Eruption record is too limited to assess eruption frequencies		
Fiji			
Samoa			

Limitations associated with the incompleteness and variability of the eruption record means that the eruption frequencies reported here represent minimum values

### 3.1 Indonesia

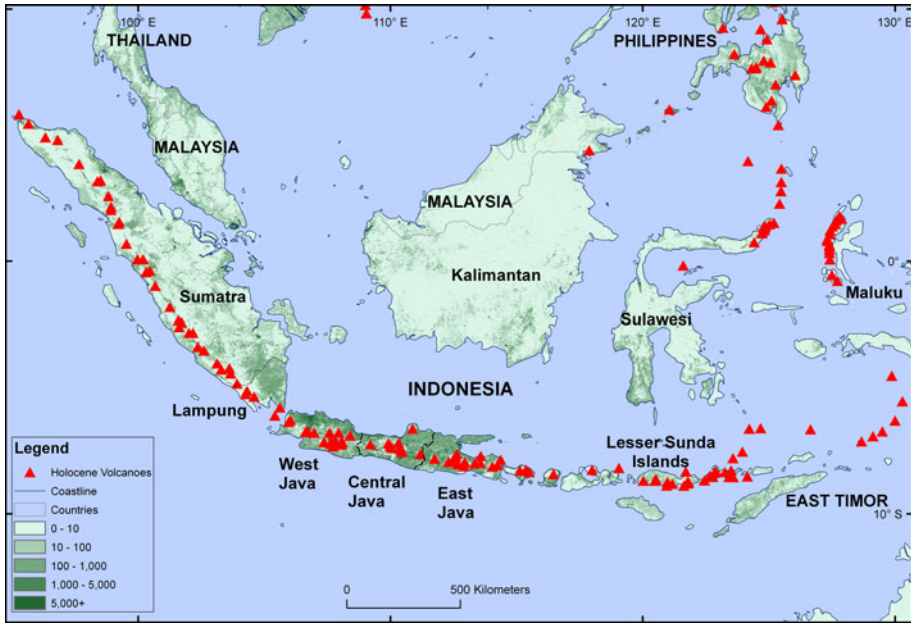
The very high frequency for large (VEI 4 or larger) eruptions—one in 14 years—in Indonesia is not unexpected, given that more than 1150 eruptions have taken place there in the last 400 years. Nonetheless, the frequency of large events in Indonesia may be even higher, as one large eruption has taken place there every 11 years on average over the last 200 years. Moreover, it is important to recognise that multiple large eruptions have occurred within short timeframes in Indonesia, such as six VEI 4 or larger eruptions recorded between 1812 and 1826.

The volcanic eruption hazard is not consistent across Indonesia. For example, dense volcano clusters in Java and northern Sulawesi contrast with volcano-free zones in Kalimantan (Indonesian Borneo) (Fig. 4). Thus, for Indonesia, it was useful to determine the frequency of large eruptions at a provincial scale (Table 2). East Java has the highest frequency at 1 in 46 years, followed by northern Sulawesi and Maluku at around 1 in 80 and 1 in 110 years, respectively. West Java, Central Java, and Bali have frequencies of around 1 in 140 years. The frequency of large eruptions in Sumatra could not be determined due to very limited data.

The high frequency of large eruptions in Indonesia has considerable implications when the populous nature of the area is considered, particularly in East Java. East Java has the highest risk if we consider how an eruption would affect Indonesia's ability to respond to a volcanic disaster, a risk that can be approximated using the percentage of a country's population exposed to the disaster. East Java contains 17% of Indonesia's population, so a large eruption here may seriously affect Indonesia's ability to respond to a volcanic disaster. In contrast, North Sulawesi has only a few per cent of Indonesia's population, so there may be more national resilience to cope with a volcanic disaster there. West and Central Java also have high volcanic eruption risk using this metric.

### 3.2 Philippines

The eruption frequency for VEI 4 or larger eruptions in the Philippines was determined to be one in 50 years. The Philippines was divided into the Northern Islands, Central Luzon, Southern Luzon, Central Philippines and Mindanao (see Fig. 5) to determine whether volcanic eruption hazard differs across the Philippines as it does with Indonesia. The frequencies for large eruptions in Southern and Central Luzon are relatively high, both



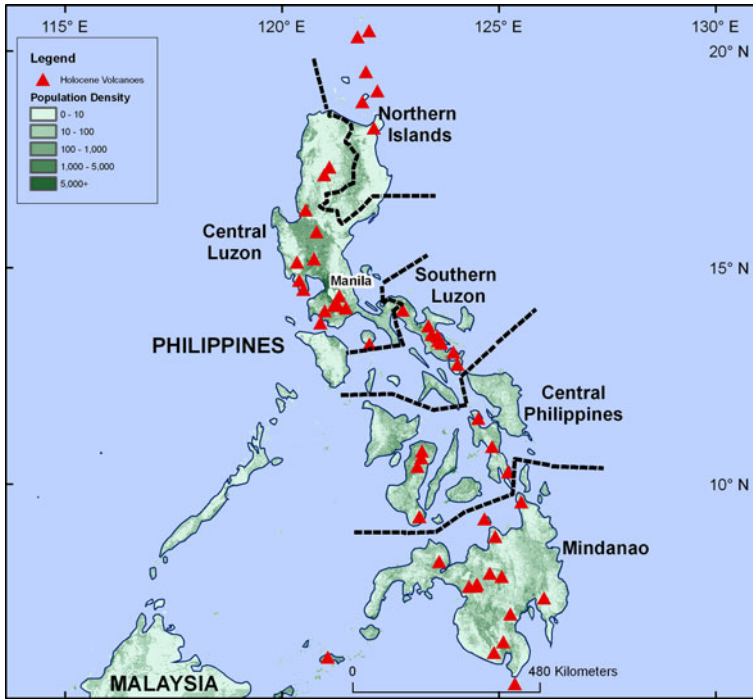
**Fig. 4** Holocene volcano locations and population density (per km<sup>2</sup>) in Indonesia

**Table 2** Frequency of large eruptions in selected Indonesian Provinces

Province	Frequency of VEI 4+ eruptions	Frequency of VEI 5+ eruptions	Frequency of VEI 6+ eruptions
East Java	1 in 46 years	1 in 278 years	1 in 1,665 years
Sulawesi	1 in 81 years	1 in 556 years	1 in 3,788 years
Maluku	1 in 108 years	1 in 526 years	1 in 2,562 years
West Java	1 in 137 years	1 in 714 years	1 in 3,732 years
Central Java	1 in 140 years	1 in 833 years	1 in 4,964 years
Bali	1 in 147 years	1 in 476 years	1 in 1,546 years
Lampung	1 in 172 years	1 in 714 years	1 in 2,959 years
East Sunda Islands	1 in 175 years	1 in 909 years	
West Sunda Islands	1 in 176 years	1 in 1,000 years	1 in 5,678 years
Sumatra	Eruption record was is too limited to assess eruption frequency		

around one in 120 years (Table 3). For VEI 6 or larger eruptions, Central Luzon appears to have a considerably higher risk than Southern Luzon. However, this result may be an artefact of the very limited historical dataset available for large eruptions in the Philippines. These areas also have a relatively high number of volcanoes without eruption chronologies, so the actual frequencies will be higher. The frequency for the Central Philippines and Northern Islands could not be calculated due to limited data.

A combination of relatively large population and high volcanic hazard produces high eruption risk in the Philippines. In fact, Central Luzon is one of the highest risk areas in the Asia–Pacific region. The impact of large eruptions in this region was well illustrated by the



**Fig. 5** Holocene volcano locations and population density (per km<sup>2</sup>) in the Philippines

**Table 3** Frequency of large eruptions in regions of the Philippines

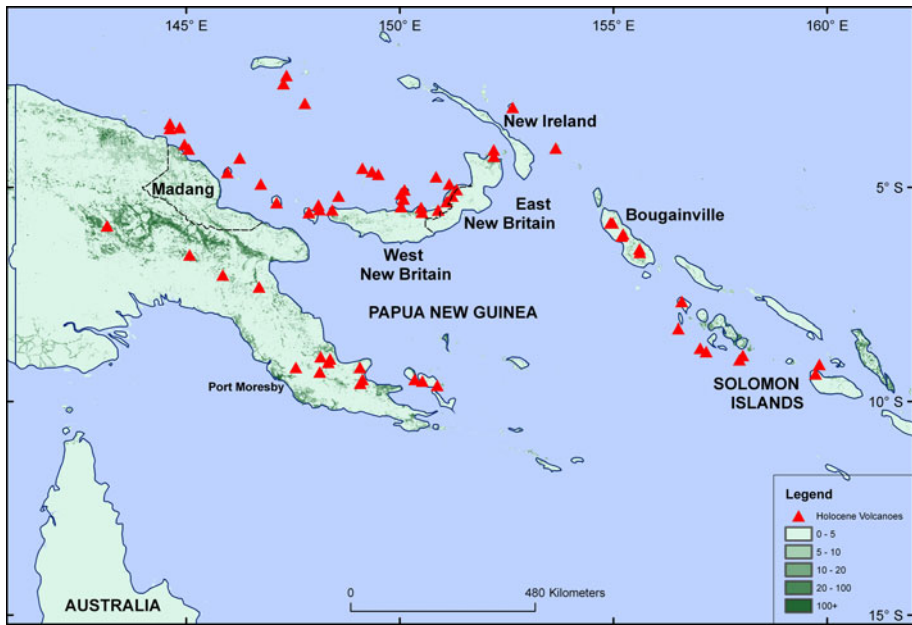
Region	Frequency of VEI 4+ eruptions	Frequency of VEI 5+ eruptions	Frequency of VEI 6+ eruptions
Southern Luzon	1 in 117 years	1 in 769 years	1 in 5,044 years
Central Luzon	1 in 122 years	1 in 435 years	1 in 1,545 years
Mindanao	1 in 196 years	1 in 1,000 years	1 in 5,096 years
Central Philippines	Eruption record is too limited to assess eruption frequencies		
Northern Islands			

Pinatubo eruption of 1991 when damage to crops, infrastructure and personal property, and business losses totalled more than \$US461 million for 1991–1992 (Mercado et al. 1996). In addition, the eruption slowed the region’s growth and altered key development activities and priorities.

### 3.3 Papua New Guinea

Based on frequency–magnitude assessments, a VEI 4 or larger eruption is expected once every 25 years in Papua New Guinea. This frequency certainly represents a minimum value, as there have been 11 VEI 4 or larger eruptions since 1800. Moreover, there have been three VEI 4 eruptions in Papua New Guinea in the last 6 years. Clusters of volcanic eruptions are also noted in Papua New Guinea from 1951 to 1957 and from 1972 to 1975.





**Fig. 6** Holocene volcano locations and population density (per km<sup>2</sup>) in Papua New Guinea and the Solomon Islands

New Britain and coastal areas along the northern New Guinea mainland have the highest volcanic eruption hazard (Fig. 6). West New Britain Province has large eruptions at a frequency of one in 69 years (Table 4). The frequency in East New Britain is one in 200 years. Furthermore, New Britain as a whole has the highest concentration of Holocene calderas in the Asia–Pacific region, so it should be considered as having a high potential for a regional-scale disaster. The province of Madang has the second highest frequency for large eruptions at around one in 90 years. This eruption hazard is concentrated off the coast and is driven by prolific activity from the volcanic island of Manam, and to some extent of Karkar and Long Islands. It is worth noting that eruptions from these offshore volcanoes are understood to have severely impact populations on mainland New Guinea in the past (Blong 1982). The frequency for large eruptions on Bougainville is around one in

**Table 4** The frequency of large eruptions in selected Papua New Guinea Provinces

Province	Frequency of VEI 4+ eruptions	Frequency of VEI 5+ eruptions	Frequency of VEI 6+ eruptions
West New Britain	1 in 69 years	1 in 385 years	1 in 2,156 years
Madang	1 in 87 years	1 in 526 years	1 in 3,171 years
Bougainville	1 in 176 years	1 in 1,111 years	1 in 7,011 years
East New Britain	1 in 200 years	1 in 1,000 years	1 in 5,001 years

There was insufficient data on eruption records to assess the frequency of eruptions from volcanoes on mainland Papua New Guinea

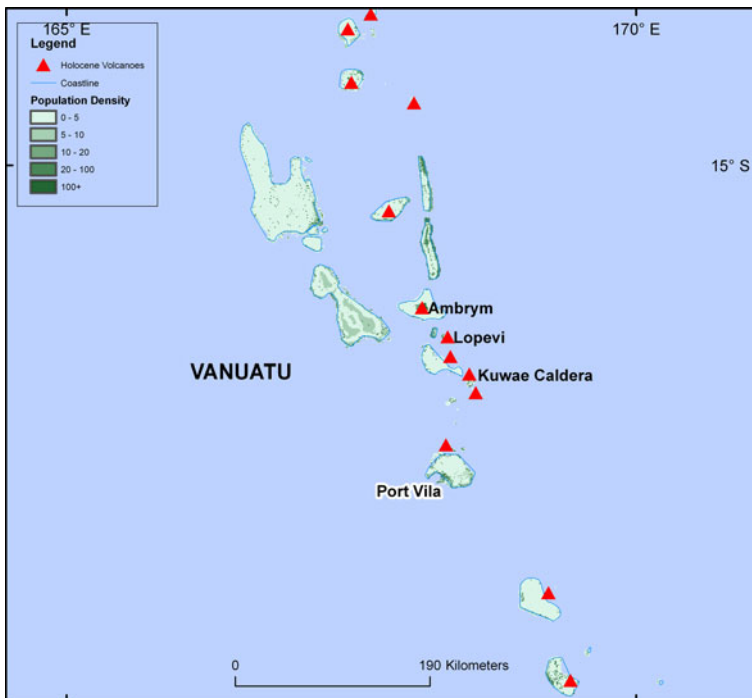
175 years. A line of volcanoes cuts through the southeastern part of the mainland of New Guinea (Fig. 6), but most of these volcanoes do not have adequate eruption chronologies and so the eruption frequency could not be determined.

Papua New Guinea has a relatively low volcanic risk because of its relatively small and well-distributed population, particularly when compared to Indonesia and the Philippines. Nonetheless, townships adjacent to the Rabaul volcano and communities in West New Britain face high volcanic risk, particularly given relatively high population densities near the calderas of Pago and Dakataua.

### 3.4 Vanuatu

The frequency for large eruptions in Vanuatu is high, around one in 40 years, meaning this island nation faces a significant volcanic eruption hazard. The most recent large eruption was a VEI 4+ eruption in 1951, but VEI 6 and VEI 6+ eruptions have taken place in the last 2,000 years (Siebert and Simkin 2002). Such large eruptions today would be catastrophic as populated areas are only a short distance from those volcanoes that have produced the largest eruptions in the past, such as Ambrym and Kuwae (Fig. 7).

Vanuatu also has a VEI 3 eruption about every 3 years, which can have considerable impact on neighbouring communities. A VEI 3 eruption at Lopevi volcano in June 2001 is reported to have deposited almost 20 cm of ash on the nearby islands, polluting open water supplies and extensively damaging staple and cash crops (Siebert and Simkin 2002).



**Fig. 7** Holocene volcano locations and population density (per km<sup>3</sup>) in Vanuatu. Selected volcanoes mentioned in text are labelled

## 4 Determining populations at risk from volcanic eruptions

### 4.1 Population data and methodology

The LandScan 2004 Global Population Database (Oak Ridge National Laboratory) was used in this study to determine populations within particular distances to volcanoes in the Asia–Pacific region. The Landscan database contains worldwide population estimated on a  $30'' \times 30''$  (about  $1 \text{ km} \times 1 \text{ km}$ ) grid made using best available census counts and supplemented by other criteria.

There are wide differences in the extents and ways in which volcanic eruptions can impact humans, but a fundamental characteristic is that, in general, people closest to the source of an eruption will be impacted more seriously than those farther away. This has been taken into account in this study by considering the average populations within different threshold distances from volcanoes in Indonesia, the Philippines, Papua New Guinea, Vanuatu, and Tonga.

The threshold distances chosen for this analysis are 15, 25, and 50 km for eruptions of VEI 4, 5, and 6, respectively. These distances represent only rough distances at which around 10–20 cm of tephra may fall and cause damage to approximately one-third of buildings (Blong 2000). Furthermore, such an ash thickness would likely result in prolonged loss of access to essential services, significant damage to agriculture, horticulture, and industry and cause severe respiratory problems. Populations within these threshold distances therefore will be seriously impacted by eruptions of corresponding VEI, where ‘seriously impacted’ is understood to mean risk of death and injury, loss of access to basic services (e.g., water, electricity), and/or complete failure of food and industrial production. The results of the above analysis are tabulated in Appendix 3 (Electronic supplementary material).

This analysis suffers from shortfalls. First, only tephra fall has been considered in establishing the threshold distances from volcanoes for different size eruptions. There are many types of volcanic hazards, but ash fall is certainly the most widespread and therefore is the most likely one to affect people’s lives and livelihoods. Second, tephra fall is assumed, on average, to fall in a perfect circle around the volcano in our coarse analysis and does not take into account wind direction and speed. Finally, the impact of a volcanic eruption can differ dramatically, including for example the degree of precursory activity and the effectiveness of monitoring, early warning, and evacuation procedures. Also, our broad definition of ‘impact’ does not discriminate between death, injury, and loss of access to basic services. Nevertheless, our results provide a useful consistent summary of the current status of populations at risk from volcanic eruption in several developing countries in the Asia–Pacific region and thus supports more targeted disaster risk reduction activities.

### 4.2 Results

Indonesia and the Philippines have the largest at-risk populations per volcano. For both of these countries, on average about 0.17, 0.5, and 2 million people live within 15, 25, and 50 km of an active or potentially active volcano, respectively. Papua New Guinea, Vanuatu, and Tonga have far lower sizes of at-risk populations per volcano. However, considered as a percentage of population—which could relate to the country’s overall capacity to respond to a volcano disaster—the profile of at-risk population per volcano changes considerably. Vanuatu is the only country in the Asia–Pacific region with 1% or greater of its national population within 15 km of an active or potentially active volcano.

Thus, a VEI 4 eruption may be large enough to seriously affect 1% of the population. Indonesia and Philippines have 1–2% of their population vulnerable to a VEI 6 eruption (i.e. within 50 km), and Tonga and Vanuatu have 4–6% of their populations vulnerable to a VEI 6 eruption. A well-distributed population in Papua New Guinea may mean that it is less vulnerable overall to volcanic eruptions. However, in terms of responding to a volcanic disaster—a risk metric not investigated in this study—Papua New Guinea may be one of the most vulnerable, as remote communities are commonly accessible only by air.

Summary profiles have been produced in order to illustrate the impact and frequency of large volcanic eruptions in the Asia–Pacific region, both in terms of absolute population (Fig. 8a) and percentage population (Fig. 8b). In broad terms, the results can be summarised as follows:

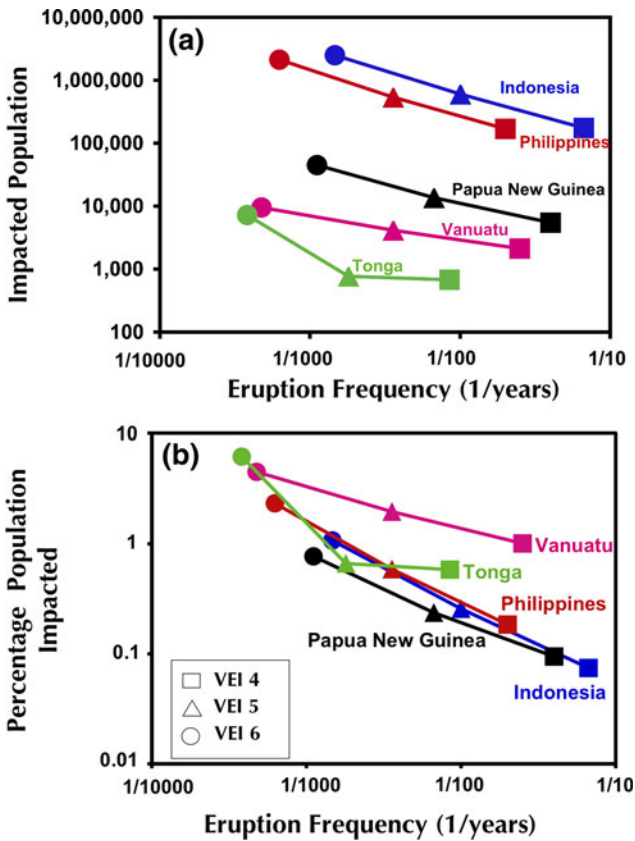
- Volcanic disasters impacting populations of 100,000 or more can be expected at least once every decade in Indonesia and around once every few decades in the Philippines.
- All of the countries for which results were obtained—Indonesia, the Philippines, Papua New Guinea, Vanuatu, and Tonga—have the potential for a catastrophic volcanic disaster (one which impacts at least 1% of the population), at a rate of at least twice a century for Vanuatu, around twice a millennium for Indonesia and the Philippines, and once every millennium for Papua New Guinea and Tonga.
- Vanuatu has the potential for a volcanic catastrophe that impacts more than 5% of its population, with a frequency of about once every 1,000 years.

## 5 Discussion and concluding remarks

The above at-risk population results appear high compared to the historical experience of volcanic eruptions, and indeed we acknowledge that our analysis of necessity has limitations. A consideration of the projection of the VEI 7 eruption at Tambora in 1815 to the present day in Fig. 9 serves to highlight some of the uncertainties involved.

VEI 7 eruptions have a global frequency of about twice a millennium (Simkin and Siebert 1994). Only one-third of the world's VEI 7 have taken place in the Asia–Pacific region, and some of these were in Indonesia, so the frequency of VEI 7 eruptions in Indonesia, such as at Tambora, could be estimated at approximately one in 3,000 years. Extrapolation of the impact frequency curve for Indonesia given in Fig. 8a is indicative of an at-risk population of 7–8 million for a VEI 7 eruption. On the one hand, for a repeat of the 1815 Tambora eruption, there are an estimated 8 million people living within the >20-cm ash fall area (Fig. 9), so this estimate of impacted population seems reasonable.<sup>2</sup> On the other hand, if such a VEI 7 eruption had taken place in Central Java, most of Java could lie within the 20-cm ash fall area, affecting well over 50 million people—that is, more than five times greater than our estimate in Fig. 8a. The coarse approximations and assumptions involved in this analysis may lead to large errors in the numbers of people affected by a single event, but the idea that tens of million people may be seriously impacted by a massive (VEI 7) volcanic event in Indonesia roughly once in 3,000 years does not seem unreasonable. In particular, it supports the conclusion that the twentieth-century population explosion in developing countries exposed to high volcanic activity may lead to disasters

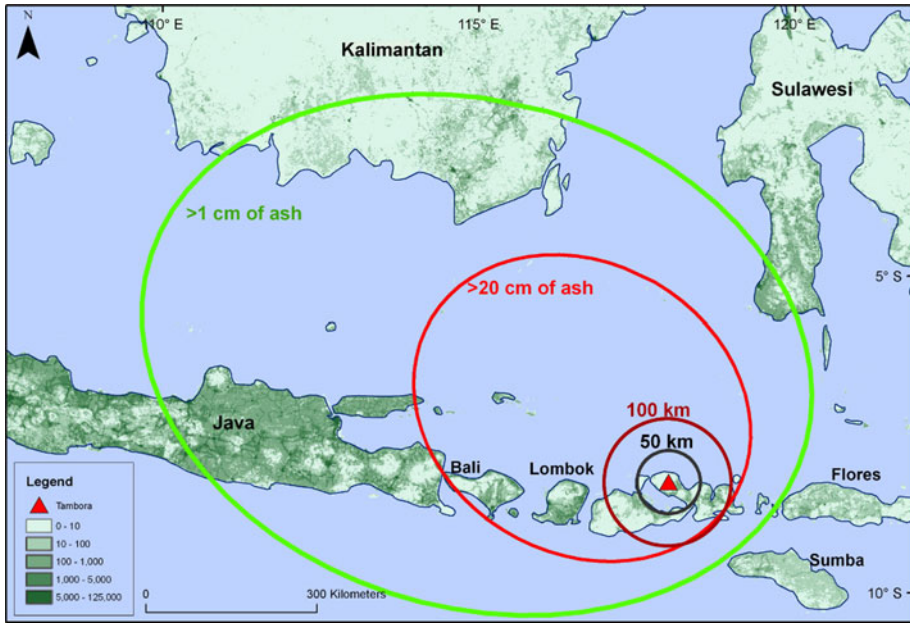
<sup>2</sup> It should be noted that the 1815 Tambora eruption is unlikely to be repeated at Tambora in the short-term; however, this example does provide an illustration of the possible impact of an eruption of this magnitude elsewhere.



**Fig. 8** Impact–frequency plots for VEI 4, VEI 5, and VEI 6 eruptions for Indonesia, the Philippines, Papua New Guinea, Vanuatu, and Tonga. **a** Frequency versus total population seriously impacted. **b** Frequency versus the percentage of a country’s population seriously impacted

having impacts on population measured in the millions, rather than the tens of thousands impacted in large historical eruptions.

A crucial aspect in this assessment of disaster risk is the metric used to define a past disaster and therefore the risk of future disasters. Typically, the number of fatalities is used to classify a disaster. However, this simplistic metric ignores other variables such as the number of displaced people, the requirement for international humanitarian assistance, and/or the economic impact of a disaster. A deliberately vague risk metric—‘seriously impacted’ or ‘at-risk’ population—was used for this study; however, future work to improve our understanding of the risk from volcanic eruption in the Asia–Pacific region will need to test different risk metrics. For example, there would be great value in calculating risk in terms of the numbers of predicted fatalities and injured if evacuation does not take place, and if it does, the probable extent of building destruction for different eruptions, the period of compromised access to essential services (water, electricity, communication, health), the impact on food supply (e.g., would the annual harvest be destroyed by ash fall?), and/or the effect on the local or regional economy. A final question is, how should volcanic eruption probabilities be assessed, such as is required for a



**Fig. 9** Tephra fall from the 1815 VEI 7 eruption of Tambora projected onto the present-day population of Indonesia. About one million people currently live within 100 km of the volcano, eight million people currently live within the >20 cm tephra isopach, and a further 70 million people—one-third of the Indonesia's population—live within the >1-cm tephra isopach. Ash dispersal data from Self et al. (1984)

meaningful risk assessment, in a region where eruption records are either incomplete or absent? Clearly, a greater effort needs to be made to determine many more, and refine existing, eruption chronologies for volcanoes in developing countries within the Asia–Pacific region. An improved understanding of volcanic eruption risk at regional and national scales will in turn support the prioritisation, and implementation of, volcanic hazard risk analysis, and mitigation initiatives at high risk volcanoes.

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