Indonesia encompasses one of the most active tectonic regions on Earth. Its territory includes over 18 000 km of major tectonic plate boundary, more than twice that of Japan or Papua New Guinea (Fig. 1). This includes: the Great Sumatran Fault, at 1900 km length about 50 per cent longer than the San Andreas and North Anatolian faults; a 6000 km length of convergent plate margin, stretching from off Sumatra to the Banda Sea that has experienced the world’s second largest megathrust earthquake (Stein & Okal 2005) and its largest intraslab earthquake (Osada & Abe 1981); and one of the highest-curvature subduction zones in the world, with the Banda Arc curving through 180° in 2200 km of its length. Indonesia is home to at least 127 active volcanoes, more than any other country in the Asia-Pacific. These eruptions include three of the largest and deadliest in human history: 1257 Rinjani (VEI 7, fatalities unknown; Lavigne et al. 2013), 1815 Tambora (VEI 7, 71 000 fatalities; Oppenheimer 2003), 1883 Krakatau (VEI 6, 36 000 fatalities; Self & Rampino 1981). Other remarkable features of Indonesia’s tectonic environment are the divergent double subduction of the Molucca Sea Plate resulting in arc–arc collision (Widijayanty et al. 2003); the subduction of continental lithosphere in the Banda Sea arc–continent collision (Fichtner et al. 2010); one of the world’s youngest orogenies along the Timor–Tanimbar section of the Banda Arc (Kaneko et al. 2007; Keep & Haig 2010); and areas of pronounced mud volcano activity (Milkov 2000).

Indonesia’s pronounced tectonic activity poses a grave threat to its large and often vulnerable population. By population Indonesia is the fourth largest country in the world, with a population expected to grow from 238.5 to 305.7 million between 2010 and 2035 (Indonesian Bureau of Statistics 2014). Almost 50 per cent of Indonesians live on the island of Java, the world’s most densely populated island. Java accounted for over 60 per cent of Indonesia’s urban land use in 2010 and is expected to accommodate 80 per cent of Indonensia’s urban expansion between 2000 and 2030 (Muis et al. 2015). As noted for buildings in Banda Aceh following the 2004 Great Sumatra Earthquake (Saatcioglu et al. 2006), urban residential construction in Indonesia often comprises low-rise, non-engineered structures that are unable to withstand the loads that might be placed on them by a major event such as an earthquake, tsunami or volcanic eruption. From the combination of increased population, greater urbanization and poor construction standards, we can expect that Indonesia’s vulnerability to natural hazards is high, much higher than it has ever been in the past.

Because geological hazards in Indonesia comprise a potent threat to a large and vulnerable population, it is important that decisions made by disaster managers be informed by the best available Earth science. Considerable progress has been made in recent years in providing the Earth science that can support disaster risk reduction, and it is the purpose of this Geological Society of London Special Publication to document some of this progress.

Tsunamis

The vulnerability of Indonesia to tsunamis was starkly illustrated by the 2004 Indian Ocean Tsunami (IOT), which killed over 165 000 people along the coast of northern Sumatra. This single event, the most lethal tsunami disaster in human history, accounts for almost 70 per cent of the recorded deaths due to natural disasters in Indonesia since 1900 (Fig. 2). While it may be tempting to regard this event as unique and therefore unrepresentative of the type of tsunami impact Indonesia will experience in the future, it is important to remember that the 1883 eruption of Krakatau generated a tsunami that killed tens of thousands. Also, in this issue Harris & Major (2016) use the historical catalogue of Wichmann (1918) to highlight the many destructive tsunamis that have occurred historically in eastern Indonesia during the colonial period (seventeenth to nineteenth centuries). They point out that the past 160 years has been a time of relative quiescence, but that if the previous level of activity resumes it will have a much greater potential for disaster now than in the past because of the explosive growth in population during the twentieth century.
Fig. 1. Active tectonics of the Indonesian Region. Major plate boundaries are indicated: subduction zones and back-arc thrusts by the black and green ‘toothed’ curves, respectively; plate boundaries with uncertain relative movement by grey curves; and other transform boundaries by red curves. Also indicated are Holocene volcanoes (red triangles) and the absolute motion of the Australian Plate and the Sunda Arc. Plate boundaries are from Bird (2003); volcanoes from Global Volcanism Program (2013).

Fig. 2. Impacts of natural disasters occurring in Indonesia from 1900 to 2016 in terms of (a) fatalities and (b) people affected. Data from the EM-DAT database (Guha-Sapir et al. 2017).
Understanding just how large the impacts of future tsunami events might be requires careful modelling of tsunami inundation that takes into account the wide variety of rupture styles of tsunamigenic earthquakes. Griffin et al. (2016) have undertaken such a study using the highly probable scenario of a tsunamigenic earthquake off Padang, Sumatra, as a case study. In this case there are considerable palaeogeodetic data that can be used to constrain the range of plausible rupture scenarios, and Griffin et al. (2016) show that sampling a range of such scenarios yields more robust estimates of which areas may be inundated than does considering any single scenario. The challenge in future tsunami hazard assessments will be to determine how a range of plausible scenarios can be considered when there are few if any data to constrain them.

Earthquakes

Figure 2a shows that, following the massive fatalities caused by the 2004 IOT, earthquakes are the second largest source of natural disaster fatalities, accounting for 12.5 per cent of the total (about 40 per cent if the IOT is discounted). The sequence of large earthquakes that ruptured the Sumatran subduction zone since 2004 has called attention to the potential for damaging earthquakes to occur in Indonesia. Historical records prior to 1900 indicate that this level of activity is not unusual, and that while the largest Sumatran events of the 1700–1800s have largely repeated themselves since 2004, historical events in Java and eastern Indonesia have not, that is, the post-1900 occurrence of large earthquakes in Java and eastern Indonesia has been low by historical standards (Nguyen et al. 2015). As was true for tsunamis, the exponential growth in population in the late twentieth century means that the impact of these events when they recur will far exceed their historical levels. Therefore, there is an urgent need to improve our understanding of earthquake hazard and risk in Indonesia. The studies published in this issue deal with several aspects of earthquake risk: earthquake sources, ground motion and site response, fatality models and probabilistic seismic hazard assessment.

Sources of earthquakes

Most of the known damaging Indonesian earthquakes have occurred in the pre-instrumental, historical past. The difficulty in assessing the threat they pose to present-day populations is exacerbated by the fact that most of them cannot be unequivocally associated with specific faults. Indeed, very few of the many known crustal faults in Indonesia have been conclusively categorized as active. In this Special Publication, Harris & Major (2016) have made important progress in identifying the faults associated with some of the most damaging earthquakes known to have occurred during the colonial period (seventeenth to nineteenth centuries). In another paper Watkinson & Hall (2017) have taken a more systematic approach by using geological methods to identify active faults in eastern Indonesia. Of the 27 faults they studied, 16 show rapid and three show low tectonic activity. Watkinson & Hall (2017) call particular attention to the Palu-Koro Fault in Sulawesi, which they characterized as having a high slip rate with fault strands proximate to a large urban population in the city of Palu.

Probabilistic seismic hazard assessment

In order to inform engineering requirements for seismically resilient construction, a hazard assessment needs to specify exceedance levels of ground motion for different return periods and frequencies of wave motion. The only widely accepted approach for estimating these is probabilistic seismic hazard assessment (PSHA), which has been used to support the Indonesian building code since at least 2002 (SNI-1726). A revision to the national-scale bedrock PSHA was undertaken in 2010, and another is currently underway. These more recent national PSHAs generally involve much higher levels of hazard due to the inclusion of active crustal faults, but the earthquake potential for these faults is often poorly determined. Omang et al. (2016) in this Special Publication show how this uncertainty, specifically in the estimated fault slip rate and locking width, can be directly incorporated into PSHA so that hazard assessment results more robustly reflect the quality of information used as input, although this methodology has yet to be incorporated in any Indonesian PSHA.

The Indonesian Geological Agency has also developed province-scale PSHAs that include site amplification, and Cipta et al. (2016) in this Special Publication present an example of this work for the six provinces of Sulawesi. As suggested by Watkinson & Hall (2017), the hazard levels in the city of Palu are alarmingly high: the 10 per cent in 50 years exceedance levels of ground motion are about 1 g for Peak Ground Acceleration (PGA); 2.5 g for 0.2 s Response Spectral Acceleration (RSA); and about 1.5 g for 1.0 s RSA. Cipta et al. (2016) compare two widely used proxy-based approaches for estimating site class with site classes determined at selected sites using in situ measurements of the average shear velocity in the top 30 m of the soil profile (Vs30). This comparison shows that these three methods of determining site class can often give inconsistent results. While this suggests considerable uncertainty in the estimated
ground motion exceedance levels, the extremely high levels of hazard argue for much more work to be done in Palu in order to help prioritize the improvement and to enforce the building codes of that city.

**Earthquake site response and ground motion**

Site response is an important consideration, not only in Palu but throughout Indonesia, due to the pervasiveness of poorly consolidated sediments in the surface geology, as these can act to greatly amplify earthquake ground motion. In this Special Publication Ridwan et al. (2016) report on an extensive survey of the shallow shear-wave velocity structure of the Jakarta Basin, home to Indonesia’s largest city and capital, Jakarta. With a population that has recently topped 10 million, the city of Jakarta itself now ranks as a megacity. However, the combined population of Jakarta and its neighbours Bogor, Depok, Tangerang and Bekasi (popularly known as ‘Jabodetabek’) is over 28 million, making it one of the world’s great urban agglomerations. Most of these people live in the Jakarta Basin, with a surface geology of alluvial sediments, beach ridge deposits and volcanic tuff. Ridwan et al. (2016) show that these materials have near-surface shear-wave velocities of 200–400 m s\(^{-1}\), corresponding mainly to National Earthquake Hazard Reduction Program (NEHRP) site classes D and E, and that material with shear velocity <750 m s\(^{-1}\) extends to considerable depth, from 350 m in the south to 725 m in the north. Such low-velocity sediments near the surface combined with the considerable depth of the sediment column suggests a complicated resonance structure that may affect high-rise buildings as well as low-rise residential structures.

Nothing contributes more to the understanding of the ground motions that may be experienced in future Indonesia earthquakes than observations of actual ground motions recorded following past earthquakes. Such recordings have only recently become available in Indonesia, thanks to the deployment of an extensive network of strong motion recording instruments as part of the massive investment in earthquake monitoring infrastructure that followed the 2004 Great Sumatra Earthquake. In this Special Publication, Pramono et al. (2016) describe the implementation of real-time ‘ShakeMaps’ within Indonesia’s Agency of Meteorology, Climatology and Geophysics (BMKG). These are intended to support rapid response following the occurrence of a large, damaging earthquake, but Pramono et al. (2016) also show that recorded ground motions are generally consistent with theoretical models.

**Earthquake fatality model**

Ultimately, in order to make informed decisions regarding earthquake mitigation, public officials need to understand not only the hazard — that is, the potential earthquake ground motion levels — but also the impact earthquakes can cause. Natural hazard impacts can be measured in a variety of ways, but one of the most important is in terms of fatalities. While other models have been developed for earthquake fatalities in the Indonesian region (e.g. Jaiswal & Wald 2010), very little consideration has hitherto been given to the assessment of model uncertainty. In this Special Publication, Sengara et al. (2017) address this issue by using a Bayesian approach to develop a fatality model that estimates both uncertainty and the expected number of fatalities for a given earthquake. The authors expect this model to be useful in rapid assessments of earthquake impact that are needed for disaster response.

**Volcanic eruptions**

Volcanoes are a major concern in Indonesia, with about 100 000 lives having been lost to volcanic disasters in the last 200 years. A statistical analysis of volcanic eruptions in Indonesia by Simpson et al. (2011) showed that volcanic disasters having an impact upon populations of 100 000 or more can be expected at least once every decade in Indonesia, and a ‘catastrophic’ event affecting over 1 per cent of the population (over 2 million based on current population) can be expected every 500 years. While fatalities have been greatly reduced due to the effective warning system established by Indonesia’s Geological Agency, not all of the 77 historically active volcanoes are monitored, nor are the over 50 volcanoes that have had no historical eruptions but are thought to have erupted in the Holocene. The potential for such volcanoes to resume activity after a long hiatus was highlighted by the recent eruption of Mt Sinabung, which had been dormant for the past 400 years.

Volcanic ash is a hazard associated with volcanic eruptions that threatens communities living in the vicinity of active volcanoes. In this Special Publication, Bear-Crozier et al. (2016) describe how they have adapted an existing open-source volcanic ash dispersion model for use in Indonesia. They used Gunung Ciremai in West Java as a case study, and considered a complete range of possible wind conditions for both dry and rainy seasons, showing that communities on the western side of Gunung Ciremai are susceptible to volcanic ash loading in any season, while communities on the eastern side are more susceptible during the rainy season. The authors suggest that disaster management officials can use this kind of detailed information on volcanic hazard to better focus mitigation efforts.
Mud volcanoes

While mud volcanoes are present in several tectonically active regions in the world (Milkov 2000), they are normally regarded as a secondary hazard associated with earthquakes, and it is rare for them to cause a significant societal impact. The Lusi mud-flow disaster in East Java is unique in this respect (Lusi is a contraction of *Lumpur Sidoarjo*, where *lumpur* is the Indonesian word for ‘mud’ and *Sidoarjo* is the name of the regency in East Java where Lusi is located). The volcano began erupting on 29 May 2006, two days after the Mw 6.3 Yogyakarta earthquake about 275 km away. To date the Lusi eruption has displaced about 40 000 people and resulted in about US$2.7 billion in economic loss. Since its initial eruption, the issue of whether it was triggered by the Yogyakarta earthquake or by drilling activity of the Lapindo oil company has been hotly debated (see, e.g. Tingay et al. 2015).

In this Special Publication, Andreas et al. (2017) analyse the ground deformation signatures of the Lusi mud volcano to help resolve this controversy. These ground motion signatures include GPS and Interferemetric Synthetic Aperture Radar (InSAR) measurements of ground deformation as well as observations of crack orientations and geophysical electric field measurements. The authors show that there is no discernible pattern in the ground motion signatures that would indicate fault reactivation, and that these signatures are instead consistent with the triggering of Lusi by the Lapindo drilling activity.

Conclusion

While it was the intention that the articles of this Geological Society Special Publication would span a wide range of geological hazards, it has not been particularly successful at doing so. The editors were unable to solicit any contribution on landslide hazards, which account for 1.1 per cent of fatalities and 1.3 per cent of people affected by natural hazards and are therefore significant (Fig. 2). Tsunamis were covered by only two papers, and volcanoes by only one paper, when clearly their importance in terms of impact (as indicated in Fig. 2) merits more attention. Instead, the Special Publication focuses strongly on earthquake hazard, which is the subject of six of the ten contributions.

Is the emphasis on earthquake hazard warranted? Does this reflect only that the science for earthquakes is well developed relative to the other hazards, or that the editors were more involved in the earthquake community than in others? We believe it is the former, and that in fact the communities of Indonesian scientists specializing in the other geological hazards – tsunamis, volcanoes and landslides – are actually quite small, despite the significant threat these hazards pose to Indonesian society.

Earthquake hazard in Indonesia is very important. As indicated in this Special Publication and elsewhere, historical records of pre-instrumental earthquake activity suggest that many more earthquakes occurred in the seventeenth to nineteenth centuries in areas of Indonesia that are now densely populated than have occurred in living memory. Given the high population density, especially in Java, and the poor construction standards, it can be surmised that the likelihood of Indonesia experiencing a major earthquake disaster in the twenty-first century is reasonably high. Furthermore, there is something we can do about it. With rapid urbanization and increasing population, as well as increasing incomes, new construction is taking place at a fast pace. If building codes can be better informed by reliable hazard estimates, and if these codes are followed, fatalities due to future earthquakes may be substantially reduced. There is every reason to believe a strong effort at better earthquake hazard assessment and mitigation will bring enormous benefits to society.

However, the editors cannot help but feel that other geological hazards, not to mention non-geological hazards, need more investment if Indonesia is to develop into a society with an acceptable level of disaster resilience. Even after the 2004 IOT killed over 160 000 Indonesians, there are still very few faculty staff at Indonesian universities who could be described as ‘tsunami scientists’. Regarding volcanoes, despite the huge social cost of evacuating large populations from the vicinity of active volcanoes on a yearly basis, and despite the potential for cataclysmic eruptions that might affect the whole region, it is difficult to identify even one Indonesian university scientist who specializes in volcanoes as a hazard (i.e. as opposed to specializing in igneous rocks). While the situation may be slightly improved in government technical agencies, we would argue that progress in the science of geohazards is best achieved by a community of academic and government scientists working together, as is the case for earthquake science in Indonesia. We therefore hope that our introduction to the Geological Society of London Special Publication on geohazards in Indonesia will help to call attention not only to the excellent work that has been done to improve our knowledge of these threats to the well-being of all Indonesians, but also to the need for more research investment in all geohazards.

Correction notice: The catchline of the original version was incorrect.
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