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ORIGINAL PAPER

Volcanic tsunami: a review of source mechanisms, past events and hazards in Southeast Asia (Indonesia, Philippines, Papua New Guinea)

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Abstract Southeast Asia has had both volcanic tsunamis and possesses some of the most densely populated, economically important and rapidly developing coastlines in the world. This contribution provides a review of volcanic tsunami hazard in Southeast Asia. Source mechanisms of tsunami related to eruptive and gravitational processes are presented, together with a history of past events in the region. A review of available data shows that many volcanoes are potentially tsunamigenic and present often neglected hazard to the rapidly developing coasts of the region. We highlight crucial volcanic provinces in Indonesia, the Philippines and Papua New Guinea and propose strategies for facing future events.

Keywords Volcanic tsunami · Volcano instability · Pyroclastic flow · Underwater explosion · Southeast Asia · Indonesia · Philippines · Papua New Guinea

1 Introduction

Tsunamis can be defined as long-period water waves generated by a sudden displacement of the water surface. This general definition is sufficiently broad to cover all possible scenarios for the generation of tsunami. Tsunami generation is generally thought of as a

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product of seismic disturbances on the sea floor with sudden sea floor disturbances attributed to submarine earthquakes, subaerial or submarine mass flows (slides), volcanic eruptions, sea floor collapse or bolide impacts in the ocean. Although it is widely known that volcanic processes can also trigger tsunamis in oceans, seas and lakes, the source mechanisms remain difficult to model because of their inherent complexity and the relative rarity of observational data (Kienle et al. 1987). The ISI Web of Science database gives more than 15,000 "volcano" references and more than 4,500 "tsunami" references since 1955. In contrast to the large number of papers on tsunami and volcanism in general, there are only 176 references listed for "volcanic tsunami", 98 % of which were published between 1995 and 2010. There are few individual scientists who work on both physical volcanology and tsunamis. Investigations on volcanic tsunamis are thus hampered by a lack of interdisciplinary expertise. Volcanic tsunamis are rarely included in volcanic hazard documents (hazard maps, evacuation plans, etc.), even though they clearly expand the potential damage area of many submarine and coastal volcanoes. Such events would occur with little warning and can cause devastation at considerable distance from the volcano. For example, fatalities from the Krakatau tsunami in 1883 occurred as far as 185 km (2 people died in Pakisjaya, northern Java: Verbeek 1886) and even 3,000 km from the volcano (one person died at Arugam, Sri Lanka: Wharton 1888).

The definition of volcanic tsunami must embrace eruptive, intrusive and gravitational processes as tsunami sources. Other terms such as "volcanogenic tsunami" (e.g. Freundt et al. 2007) or "volcanism-induced tsunami" (e.g. Nishimura 2008) are also employed. Latter (1981) gives the following definition: "Tsunami closely associated in time and space with volcanic eruptions". Begét (2000) proposed a wider definition: "A high wave or surge of water produced by a variety of eruptive and non-eruptive processes at volcanoes". Here, we consider as volcanic tsunamis *s.l.* to be all tsunamis generated by eruptive processes, rapid ground deformation and slope instability at volcanoes (Table 1).

Using this definition, volcanic tsunamis represent around 5 % of all tsunamis listed for the last four centuries (Latter 1981). At least 130 events were observed since 1600 AD, 60 of them during the twentieth century and 36 during the nineteenth century (from the catalogue of the National Geophysical Data Center—NGDC: http://www.ngdc.noaa.gov/hazard/hazards.shtml). About 20–25 % of all fatalities directly attributable to volcanoes during the last 250 years have been caused by volcanic tsunamis (Latter 1981; Auker et al. 2013). The fatalities were mostly during the 1883 Krakatau eruption in Indonesia (36,500 victims, ~95 % of them by tsunamis) and Mayuyama flank collapse in Japan (15,030 victims, ~75 % of them by tsunami). Begèt et al. (2008) suggested a link between volcanic tsunamis and prehistoric cultural changes in a region of Alaska. He highlighted the well-known example and abundant literature on the controversial impact of the LBA (Late Bronze Age) Santorini eruption and tsunami (e.g. Yokoyama 1978; Antonopoulos 1992; McCoy and Heiken 2000; Dominey-Howes 2004).

2 Source mechanisms in volcanic systems

Tsunamis of eruptive origin occur when part of the energy released during an eruption is directly or indirectly transmitted to the sea, generating impulsive waves by the displacement of water (Begét 2000). Although the phenomenon is well known, the precise nature and dynamics of the interactions and processes that generate waves during eruptions are not well understood (Latter 1981; Begét 2000; de Lange et al. 2001). Up to eight mechanisms are implied in the generation of volcanic tsunamis (Table 2): underwater

Table 1 Catalogue of volcanic tsunamis in Southeast Asia

Years	Month	Days	Country	Location	Volcano	Latitude	Longitude	Max run-up	Deaths	Cause of tsunami	Additional information	References
2007	5	19	Papua New Guinea	Bismarck Sea	Ritter Island	−5.500	148.100	10 (2)	No	Landslides?	1,500–2,000 residents evacuated	1
1994	9	19	Papua New Guinea	New Britain	Rabaul	−4.238	152.214	8 (4)	No	Pyroclastic flows		2, 3
1983	8	17	Indonesia	Lembata	Iliwerung	−8.532	123.573			Underwater explosions?		1
1981	10	20	Indonesia	Krakatau	Krakatau	−6.100	105.423	2 (4)	No	Landslide?	Subaerial activity	16
1979	7	18	Indonesia	Lembata	Iliwerung	−8.532	123.573	9 (<10)	>539	Landslide	Inundation up to 1,500 m inland	4, 17
1974	10	17	Papua New Guinea	Bismarck Sea	Ritter Island	−5.500	148.100	0.5 (10)	No	Landslide?	Tsunami of low amplitude	4, 5
1973			Indonesia	Lembata	Iliwerung	−8.532	123.573			Underwater explosions?	Formation of a new island	1
1972	10	9	Papua New Guinea	Bismarck Sea	Ritter Island	−5.500	148.100		No	Underwater explosions?	Tsunami of low amplitude	5
1969	3	21	Philippines	Luzon	Didicas	19.077	122.202		3	Underwater explosions?	3 fishermen killed (cause?)	1
1965	9	28	Philippines	Luzon	Taal	14.000	121.000	4.7 (2.5)	>150	Air waves?	Tsunami capsized boats	6
1937	5	28	Papua New Guinea	New Britain	Rabaul	−4.238	152.214	6 (2.5)	Few	Pyroclastic flows and/or explosions		7
1933	12	25	Philippines	Samar Island		12.800	124.000		9	Typhoon?	Bulusan volcano was active	7, 8
1930	3	17	Indonesia	Krakatau	Krakatau	−6.100	105.423		No	Underwater explosions		7
1928	3	26	Indonesia	Krakatau	Krakatau	−6.102	105.423		No	Underwater explosions	9 sea-level oscillations	9
1928	8	4	Indonesia	Flores Sea	Paluweh Island	−8.300	121.700	10 (15)	128	Landslide?	3 waves, 5 villages destroyed	7, 10

Table 1 continued

Years	Month	Days	Country	Location	Volcano	Latitude	Longitude	Max run-up	Deaths	Cause of tsunami	Additional information	References
1919	4	3	Indonesia	Sangihe	Banua Wuhu	3.100	125.500		No	Underwater explosions	Water rose 5 m over the volcano	7
1918	7	18	Indonesia	Sangihe	Banua Wuhu	3.100	125.500	<0.1	No	Underwater explosions		7
1911	1	27	Philippines	Luzon	Taal	14.000	121.000	3 (9)	>50	Pyroclastic surges or air waves?	All shores of the lake affected	11
1892	6	7	Indonesia	Sangihe	Awu	3.700	125.600	<1 (900)	No	Shock wave?	Tsunami in Ambon and Sumbawa	7
1889	9	6	Indonesia	Sangihe		3.100	125.500	4 (150)	No	Earthquake	Eruption of Ruang or Banua Wuhu?	7, 10
1888	3	13	Papua New Guinea	Bismarck Sea	Ritter Island	−5.600	148.100	12 (23)	500–3000	Debris avalanche	Inundation locally > 1 km inland	5, 7
1884	2		Indonesia	Krakatau	Krakatau	−6.102	105.423		No	Underwater explosion?		7
1883	10	10	Indonesia	Krakatau	Krakatau	−6.102	105.423		No	Landslide?	Inundation 75 m in Java (Cikawung)	7
1883	8	26–27	Indonesia	Krakatau	Krakatau	−6.102	105.423	37 (60)	~35,000	Pyroclastic flows		12
1878	2	4	Papua New Guinea	New Britain	Rabaul	−4.238	152.214	4 (2)	Yes	Earthquake	Underwater eruption after tsunami	7, 13
1871	4	30	Philippines	Sulu Sea	Camiguin	9.203	124.673		No	Pyroclastic flows?	Camiguin Island inundated by 1 wave	7
1871	3	3	Indonesia	Sangihe	Ruang	2.300	125.400	25 (2)	>400		Many victims at an island facing the volcano	7, 10
1857	4	17	Papua New Guinea	New Guinea		−5.059	147.875		Yes	Earthquake?	A volcano rose from the water near Umboi	7, 13
1856	3	2	Indonesia	Sangihe	Awu	3.700	125.600		Few	Pyroclastic flow		7
1845	2	8	Indonesia	Sulawesi		1.108	124.725		118	Earthquake?	VEI 2 eruption of Soputan volcano	7, 10

Table 1 continued

Years	Month	Days	Country	Location	Volcano	Latitude	Longitude	Max run-up	Deaths	Cause of tsunami	Additional information	References
1840	2	14	Indonesia	Halmahera	Gamalama?	0.800	127.325				No earthquake	7
1815	4	10	Indonesia	Sumbawa	Tambora	−8.200	118.000	3.5 (60)		Pyroclastic flows	Island subsidence 5–6 m	7, 14
1754	5	13	Philippines	Luzon	Taal	14.000	121.000		<10	Pyroclastic flows	4 villages destroyed	15
1749	8	11	Philippines	Luzon	Taal	14.000	121.000			Pyroclastic flows?	Waves in northern basin of the lake	15
1716	9	24	Philippines	Luzon	Taal	14.000	121.000			Underwater explosions	Waves lashing the SE shores of the lake	15
1673	8	12	Indonesia	Halmahera	Gamkonora	1.375	127.520		Yes	Earthquake and landslides	Landslides and rock falls for 2 months	1, 7, 10
1660			Papua New Guinea	New Guinea	Long Island	−5.358	147.120		Yes	Pyroclastic flows?	Approximate date (±20 years)	1
1659	11	11	Indonesia	Banda Sea	Teon	−6.900	129.200	1.5 (360)		Pyroclastic flows?	Wave observed in Ambon Bay	7
1608	7	1	Indonesia	Halmahera	Gamalama?	0.800	127.325		Yes		Ships run aground on the reef	1, 7
1550			Indonesia	Halmahera	Makian	0.325	127.400				Approximate age, uncertain event	1

Death toll includes only victims from tsunami (not from eruptive processes). Maximum run-up (in metres) is given at a known distance from the volcano (in kilometres)

1: GVP database (Global Volcanism Program of the Smithsonian Institution); 2: Blong and McKee (1995); 3: Nishimura et al. (2005); 4: Soloviev et al. (1992); 5: Cooke (1981); 6: Moore et al. (1966); 7: Soloviev and Go (1974); van Padang (1953); 9: Stehn (1929); 10: Berninghausen (1969); 11: Maso and Saderra (1911); 12: Verbeek (1886); 13: Everingham (1977); 14: Stothers (1984); 15: Maso and Saderra (1904); 16: Camus et al. (1987); 17: Lassa (2009).

explosions, pyroclastic flows and lahars entering the water, earthquake preceding or during a volcanic eruption, flank failure (from rock falls to massive debris avalanches), collapse of coastal lava bench, caldera collapse (resulting in rapid subsidence of the sea floor) and shock wave produced by large explosion (by coupling between shock wave and sea wave, as for meteorological tsunamis). As suggested by documented examples of volcanic tsunamis, it is unlikely that shock waves, lahars and collapses of lava bench can give birth to tsunamis with wave heights of more than 3 m (Table 2). Pyroclastic flows, flank failures and caldera subsidence are the only source mechanisms likely to imply volumes larger than 1 km^3 (Table 2).

An additional complication in the field of volcanic tsunami comes from the fact that several tsunamigenic processes can be associated, thus complicating the interpretation of observational data (such as tide gauge records) and the determination of input parameters for numerical simulations. For instance, caldera-forming eruptions such as the 1883 Krakatau and LBA Santorini eruption may involve five tsunamigenic processes: pyroclastic flows, underwater explosions, earthquakes, caldera subsidence and failures of the caldera walls. Given all these source mechanisms and their possible association, six type events are defined (Table 3), corresponding to different types of eruptions. The 1883 eruption of Krakatau volcano has been extensively studied and the sequence of the events widely discussed, especially the source and time propagation of the tsunamis that devastated the coasts of Sumatra and Java (Verbeek 1886; Latter 1981; Self and Rampino 1981; Yokoyama 1981, 1987; Francis 1985; Self 1992; Nomanbhoy and Satake 1995; Carey et al. 2000; Choi et al. 2003; Maeno and Imamura 2011). The controversy over the source of the 1883 Krakatau tsunamis is a good example of the problems caused by the complexity of volcanic tsunamis. Two different scales might be considered: (1) Choi et al. (2003) explained that the sea-level disturbances observed worldwide were transferred to the water from barometric perturbations in the atmosphere (volcanic explosions) and (2) Maeno and Imamura (2011) found that the computed tsunamis heights generated by a simulated pyroclastic flow with a volume of >5 km^3 and a discharge rate of 10^7 m^3/s are consistent with historical records of the 1883 Krakatau tsunamis in Sunda Strait (e.g. tide gauge record at Tandjong Priok, Jakarta harbour, Java). What happens when a pyroclastic flow enters the sea is poorly understood (e.g. Cas and Wright 1991; Legros and Druitt 2000). The important parameters controlling the interactions between pyroclastic flows and water bodies are the bulk density of the flow, its velocity and discharge rate and the angle of incidence between the flow and the water surface (Cas and Wright 1991; de Lange et al.

Table 2 Inferred source mechanisms of volcanic tsunamis

Source mechanisms	% of events	Source volume (km^3)	Volume flux (m^3/s)	Wave height[a] (m)	Travel distance (km)
Underwater explosion	25	<1	$<10^9$	<10	<200
Pyroclastic flow	20	1–200	10^5–10^8	<30	<300
Earthquake	<20			<15	<500
Flank failure	15	1–500	10^5–10^6	<100?	<6000
Caldera subsidence	10	1–100	10^6–10^8	<20	<200
Air wave	5			<3	>1,000
Lahar	<5	<1	$<10^5$	<3	<10
Collapse of lava bench	<1	<0.01	$<10^6$	<2	<10

[a] Wave height at the shoreline

2001). Watts and Waythomas (2003) discussed five wave generation mechanisms for a pyroclastic flow: steam explosion, debris flow, plume pressure, plume shear and pressure impulse. They demonstrated that the most energetic and coherent water waves are produced by the dense, basal debris flow component of the pyroclastic flow. Tsunamis generated by pyroclastic flows were recently observed during the Montserrat 1997 and 2003 eruptions (with maximum run-ups of 4 m in Montserrat and 1 m in Guadeloupe: Pelinovsky et al. 2004) and Rabaul 1994 eruption (with a maximum run-up of 8 m in Rabaul Bay: Blong and McKee 1995; Nishimura et al. 2005). It has also been proposed that littoral explosions may occur at the entrance of a hot pyroclastic flow into the water (Walker 1979; Freundt 2003).

Underwater volcanic explosions typically generate waves of short period, but run-ups inland can be locally high, especially around lakes (e.g. 19-m run-up at Karymsky Lake in 1996: Belousov et al. 2000; Torsvik et al. 2010). In such cases, damage is limited to the size of the lake basin, but as their coasts are often surrounded by high population densities, the risk is clearly evident (e.g. Nicaragua, Indonesia and Philippines). Although underwater explosions represent 20 % of the observed volcanic tsunamis, the tsunamis hazards related to such events are generally poorly documented and often neglected (Freundt et al. 2007). Best studied examples are (1) the Myojin-Sho (Japan) eruption in 1952, which generated waves with amplitudes up to 1.4 m high at 130 km from the volcano (Dietz and Sheehy 1954), (2) the numerous small tsunamis reported and sometimes photographed during explosions of Kavachi volcano in the Solomon Islands (Johnson and Tuni 1987) and (3) the Kick'em Jenny volcano in the Caribbean Sea, which caused 2-m tsunami waves at Grenada Island in 1939 (Smith and Shepherd 1993). Local tsunami waves generated by underwater explosions in the Krakatau caldera were described and photographed by Stehn (1929).

Volcano flank failures are not always associated with eruptive phases, as volcanic edifices are by their nature unstable due to structural discontinuities, hydrothermal alteration, seismicity, magmatic intrusions and high lava accumulation rates (e.g. Keating and McGuire 2000). Volcano flank failures entering the water can generate an extremely fast transfer of energy. The water surface falls under the weight of the avalanche, and in reaction to this sudden subsidence, an impulsive wave occurs which then propagates away from the source (Iwasaki 1997). Tsunamis generated by volcano flank failures represent a low-frequency but potentially very high magnitude hazard (Keating and McGuire 2000). By volume, the largest lateral collapse of an island volcano ($\sim$5 km^3) that is recorded in historical times took place during the 1888 eruption of Ritter Island (Papua New Guinea). That event produced waves that were recorded as being up to 10–15 m high at tens to

Table 3 Type events and associated source mechanisms of volcanic tsunami

Type of eruption	Type event	Earthquake	Underwater explosion	Caldera subsidence	Pyroclastic flow	Flank failure
Phreatomagmatic explosions in shallow waters	Myojin-Sho 1952 Karymsky Lake 1996					
Plinian eruption forming a submarine caldera	Krakatau 1883 Santorini LBA 3.6 ka					
Plinian eruption forming a subaerial caldera	Tambora 1815 Aniakchak 3.5 ka					
Explosive eruption with dome growth and collapse	Montserrat 2003 Paluweh 1928					
Explosive paroxysm of strombolian cone	Stromboli 2002 Tinakula 1971					
Massive flank failure	Ritter 1888 Oshima-Oshima 1741	?				

hundreds of km from the source (Cooke 1981; Ward and Day 2003). With 15,030 fatalities, the 1792 sector collapse of Mount Mayuyama and related tsunami in Ariake Bay (Kyushu Island, Unzen volcanic complex) is still considered one of the worst disasters in Japanese history. The failure was probably triggered by a strong earthquake, and the volume of the slide was about 340 $\times$ 10^6 m^3 (Mishiue et al. 1999). Pore fluid pressurisation may have also contributed to the development of the collapse structure (Siebert et al. 1987). Tsunami run-ups ranged between 8 and 24 m on the opposite side of the Ariake Bay (Tsuji and Hino 1993). The most recent damaging tsunami caused by volcano flank collapse occurred in December 2002 at Stromboli volcano, when 17 $\times$ 10^6 m^3 felt into the sea (Tinti et al. 2006). Here, the tsunami had a maximum run-up of 8 m on the coasts of Stromboli, with limited effect on the coasts at a distance of more than 200 km from the collapse (Maramai et al. 2005). In Solomon Islands, Tinakula volcano is very similar to Stromboli in terms of morphology and eruptive style, and local tsunamis due to landslides were reported in 1966 and 1971 (NGDC database) (Figs. 1, 2).

The size and volume of these historical events are all small compared to the potential failures of oceanic shield volcanoes, which are typically tens to hundreds of km^3 (e.g. Moore et al. 1989; Oehler et al. 2004; Masson et al. 2002). Marine conglomerates found at unusually high elevations in Hawaii, Cape Verde and Canary Islands were interpreted as being the result of giant tsunami waves generated by massive flank failures (Moore and Moore 1984; McMurtry et al. 2004; Pérez Torrado et al. 2006; Paris et al. 2011). The failure mechanism (e.g. discrete or retrogressive failures) is as essential to constrain as the whole volume of a landslide, because it controls the number of waves, their amplitude and thus their time of arrival (Giachetti et al. 2011; Kelfoun et al. 2010). Rheology that controls the landslide propagation has only a minor effect on the wave train produced and has only a second-order impact on the amplitude of the waves. Given uncertainties on their recurrence and mechanisms, these large-scale events are not considered in this paper.

3 Past events in Southeast Asia

In Southeast Asia, some work has already been done on volcanic tsunamis (e.g. Cooke 1981; Johnson and Threlfall 1985; Johnson 1987; Johnson and Tuni 1987; Nishimura et al. 2005; Ward and Day 2003; Silver et al. 2009), most of this on the 1883 Krakatau tsunamis (e.g. Verbeek 1886; Stehn 1929; Latter 1981; Self and Rampino 1981; Francis 1985; Simkin and Fiske 1983; Yokoyama 1987; Nomanbhoy and Satake 1995; Carey et al. 2000; Maeno and Imamura 2011; Giachetti et al. 2012). Nevertheless, the record remains incomplete, fragmentary, unpublished, localised and often carries inaccuracies and misinterpretations. Similar comments have been made at regional scales to the general tsunami record (e.g. Lau et al. 2010 on the South China Sea; Dominey-Howes 2007 for northern Australia; Løvholt et al. 2012 for eastern Indonesia and southern Philippines). Despite inconsistencies, several catalogues of tsunamis exist for Southeast Asia: Indonesia (Hamzah et al. 2000; Rynn 2002), New Guinea and Solomon Islands (Everingham 1977), Philippines and Taiwan (Berninghausen 1969; Cox 1970) and western Pacific (Soloviev and Go 1974). All these references were compiled in the NGDC worldwide database. Additional information can also be found in the database of the Global Volcanism Program (GVP: http://www.volcano.si.edu) on volcanoes and volcanic eruptions (e.g. catalogues of Indonesia and Philippines volcanoes by van Padang 1951, 1953).

At least 17 different volcanoes in Southeast Asia generated tsunamis during the last four centuries (Fig. 3). Forty events have been reported since 1550: one during the twenty-first

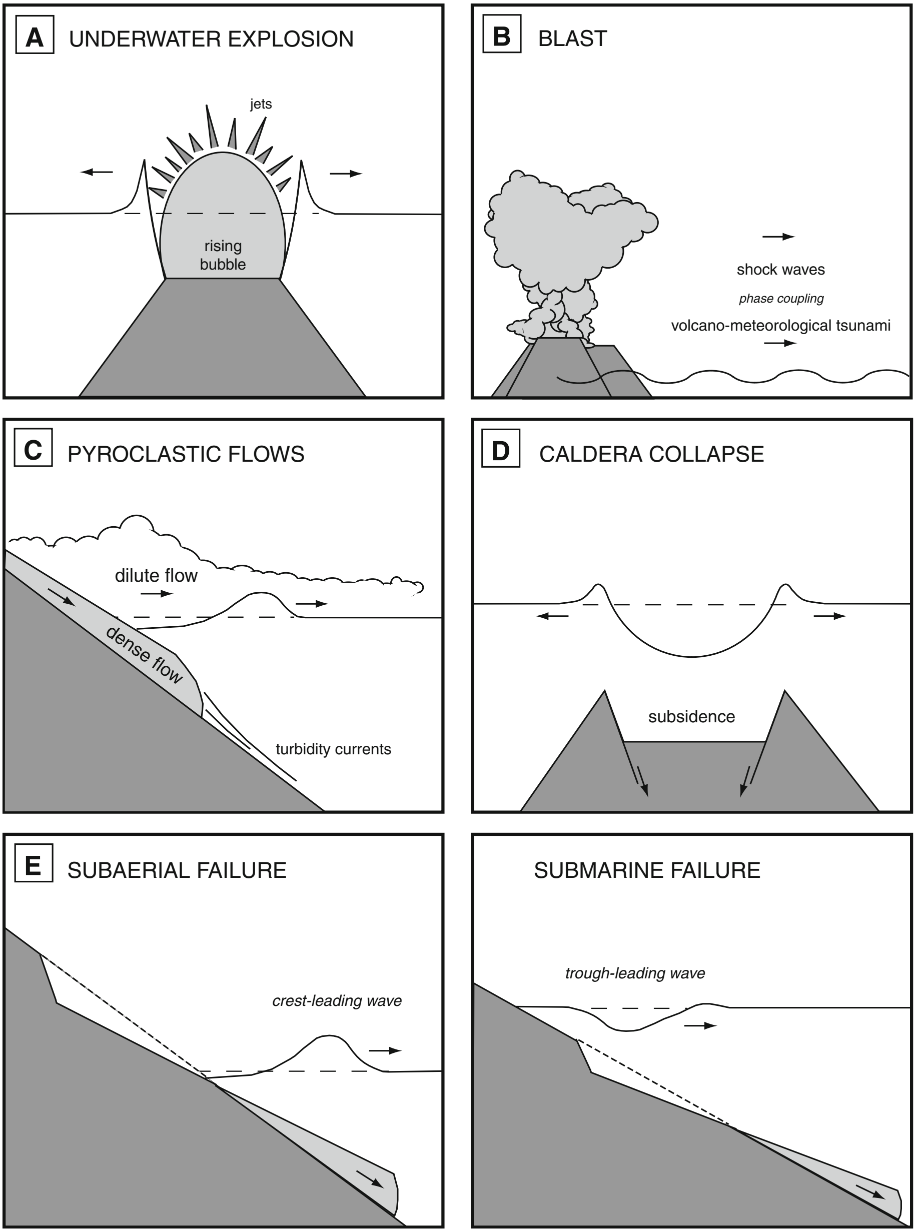

Fig. 1 Principal source mechanisms of tsunami at volcanoes: underwater explosions, air wave generated by blast, pyroclastic flow, caldera collapse, flank failures. Other mechanisms such as lahars, collapses of lava bench or volcanic earthquakes are not mentioned (see Table 2 for a complete list of source mechanisms)

century, seventeen during the twentieth century, fourteen during the nineteenth century, three during the eighteenth century, four during the seventeenth century, and one uncertain event during the fifteenth century (Table 1). The limited number of events for the eighteenth and seventeenth century is likely due to an under-reporting bias in some remote

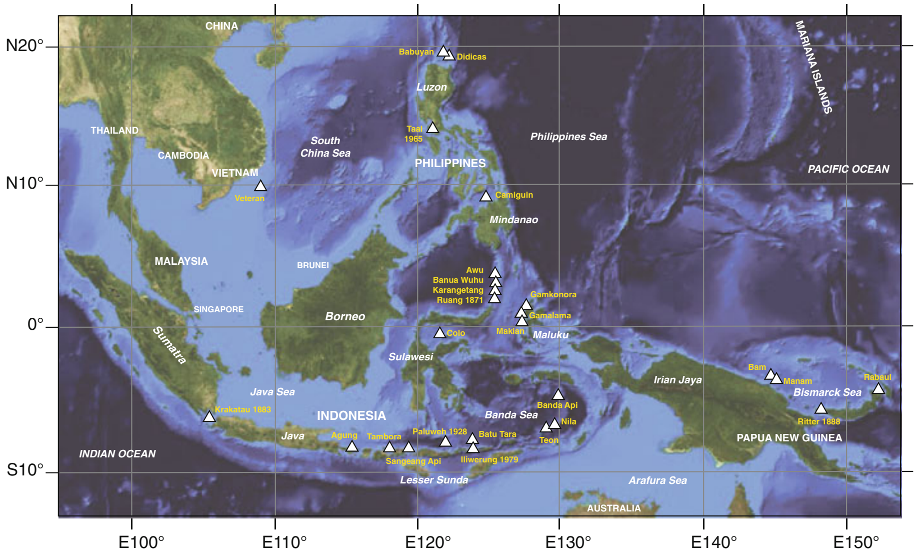

Fig. 2 Map of Southeast Asia, showing volcanoes mentioned in the text and years of most deadly volcanic tsunamis (>100 fatalities)

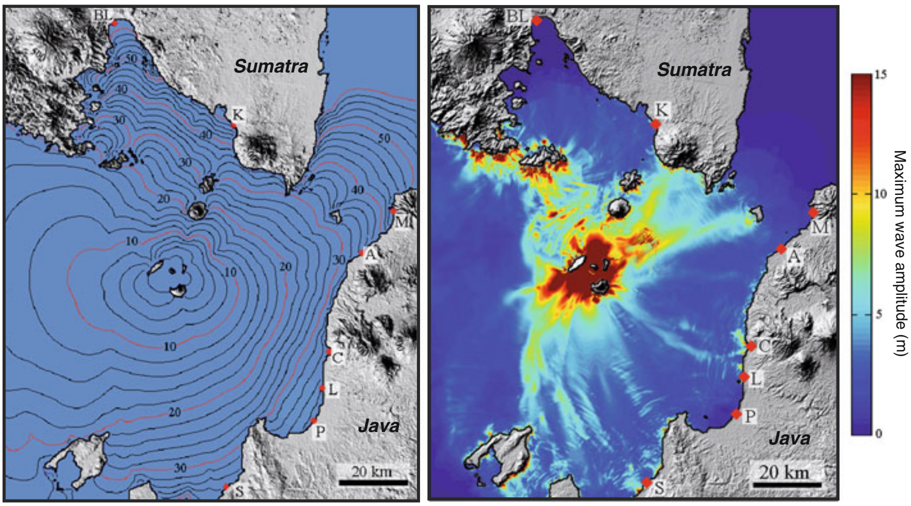

Fig. 3 Numerical modelling of a hypothetical 0.28-km^3 failure of Anak Krakatau cone. *Left* wave travel time in Sunda Strait and main coastal cities (*BL* Bandar Lampung, *K* Kalianda, *M* Merak, *A* Anyer, *C* Carita, *L* Labuhan, *P* Panimbang). *Right* Maximum wave amplitude (m) recorded over 100 min of simulation, using a constant retarding stress of 10 kPa to simulate the landslide propagation (modified from Giachetti et al. 2012)

areas (e.g. eastern Indonesia, Papua New Guinea). Three countries of Southeast Asia are affected: Indonesia (23 events), Papua New Guinea (9 events) and Philippines (8). Tsunamis were particularly frequent at Rabaul (Papua New Guinea), Iliwerung (Lembata Island, Indonesia), Taal (Luzon, Philippines) and Ritter Island (Bismarck Sea, Papua New Guinea).

Estimating the proportion of fatalities caused by tsunami during a tsunamigenic eruption is often difficult. A part from the 1883 Krakatau disaster ($\sim$35,000 people killed by the successive tsunamis), four events were particularly deadly (Table 1). The most recent disaster occurred in July 1979, when the southern flank of Iliwerung volcano (which was not active) collapsed, generating waves 7–9 m high on the surrounding coasts. The death toll ranges between 550 and 1,200 (NGDC). In March 1871, more than 400 people were killed by the 25-m-high tsunami wave at Tagulandang Island, located 4 km north of Ruang Island volcano (Soloviev and Go 1974). Tsunami occurred just at the beginning of the eruption, but the cause is not determined (pyroclastic flow, landslide). The 1888 Ritter Island and 1673 Gamkonora death tolls are uncertain given the lack of data. However, the 1888 Ritter Island tsunami death toll was estimated at between 500 and 3,000 by Johnson (1987), on the basis that at least 6 villages were completely destroyed and probably twice as many more vanished.

The cause itself of the tsunami is sometimes uncertain. For instance, earthquakes are often mentioned as the possible cause for tsunami during a volcanic eruption (e.g. Gamkonora 1673, Umboi 1857, Rabaul 1878, Sangihe Islands 1889), but it is commonly difficult to clearly constrain the different sources of tsunami waves during an eruption. Tsunami reported in Rabaul Bay in February 1878 occurred after the initial earthquake, but before the underwater eruption started (Soloviev and Go 1974). Some events are questionable (e.g. 1845 tsunami in Sulawesi) or may have been confused with storm surges (e.g. 1933 tsunami in Samar Island that was contemporaneous with a typhoon and a small-magnitude eruption of Bulusan volcano). In the NGDC database, the March 1963 tsunami in British Columbia (Canada) is surprisingly linked to the VEI 5 eruption (Volcano Explosivity Index: Newhall and Self 1982) of Agung volcano in Bali (Lesser Sunda Islands) on the basis of the Prince Rupert Daily News. This event is not included in Table 1, and there are no reports of tsunami in the proximal area (Bali and other Indonesian islands).

4 Potentially tsunamigenic volcanoes

Volcanic edifices currently considered inactive or dormant might represent a tsunami hazard only in the case of reactivation or collapse. An active volcano is considered to be potentially tsunamigenic if it satisfies one or more of the following criteria:

1. It is a steep-flanked stratovolcano with an elevated H/D ratio (with H the summit height above sea level and D the distance from the summit to the shoreline). In such cases, the main tsunamigenic mechanisms are pyroclastic flows and flank instability, from rock falls to debris avalanches. Stratovolcanoes that generated tsunamis during the four last centuries in Southeast Asia have an H/D ratio between 0.2 and 0.4 (e.g. Iliwerung, Ruang, Gamalama, Gamkonora, Camiguin, Awu, Tambora, Agung). Other examples include Lewotobi and Iliboleng in Lesser Sunda Islands (Indonesia), Makian in Maluku Islands (Indonesia), Sangeang Api in Lesser Sunda Islands (Indonesia), Banda Api, Nila and Teon in Banda Sea (Indonesia) and Mayon in the Philippines, although there are no tsunamis reported for these volcanoes in the historical record. It is of course a major simplification to consider tsunamigenic potential of stratovolcanoes in terms of H/D alone. Other physical parameters that should be considered in defining the tsunami hazard at such volcanoes include edifice volume, volume flux and density of material emplaced in previous eruptions.

2. It belongs to a coastal or partly submerged complex of eruptive centres. These complexes include lava domes, cones and maars, and caldera lakes. Potential tsunamigenic mechanisms in such systems include pyroclastic flows, phreatic and phreatomagmatic explosions from submerged vents, and small-scale flank instability (e.g. Paluweh Island). A distinction can be made between caldera lakes (e.g. Taal), calderas opened to the sea (e.g. Rabaul) and submerged calderas with emerged eruptive centres (e.g. Anak Krakatau).
3. It is a submarine edifice, especially if located in shallow waters and characterised by explosive activity. There are 18 submarine edifices identified as active during the Holocene in Southeast Asia, although it is apparent that there are many dormant volcanoes for which the hazard is unknown. Potential sites of interest here include Banua Wuhu (Sangihe Islands, Indonesia), Veteran Island (Vietnam) and the Babuyan Islands (Philippines).

5 Highlighting some potentially tsunamigenic volcanoes in Southeast Asia

Of all volcanoes that are active or have been active during the Holocene in Southeast Asia, many of them are potentially tsunamigenic (following the criteria proposed above), especially in Indonesia, Papua New Guinea and the Philippines. Neighbouring countries such as Australia and China are likely to be affected by far-field effects of tsunamis generated from volcanoes located in Indonesia, Papua New Guinea or the Philippines. To better manage the future hazard that volcanic tsunamis pose, it is necessary to review past events and evaluate present-day threat in each volcanic province. Presented in this section are a few examples of potentially tsunamigenic volcanoes. This is not an exhaustive list, but rather a few relevant examples that present the full range of tsunami producing mechanisms. Whilst this review addresses volcanic tsunami hazard rather than risk, we also briefly mention key elements related to exposure (cities and densely populated areas, economic infrastructure, communications hubs, cultural heritage sites, among other civil assets).

5.1 Anak Krakatau; Sunda Strait (Indonesia)

Krakatau still represents a tsunami hazard for the coasts of the Sunda Strait, even if the present-day activity of Anak Krakatau is limited to VEI 2 phreatomagmatic eruptions, strombolian activity and lavaflows (GVP database). Underwater explosions of new eruptive centres in the caldera, as those described by Stehn (1929), could generate tsunamis. Another hazard emerging from Anak Krakatau would be a tsunami triggered by a flank collapse, since the volcano is partly built on a steep wall of the caldera resulting from the 1883 eruption (Deplus et al. 1995). A small tsunami (approximately 2 m high) was recorded on Rakata Island in October 1981 during an awakening of Anak Krakatau (Camus et al. 1987). Giachetti et al. (2012) simulated a hypothetical 0.28-km^3 flank collapse in this system directed south-westwards. The simulated tsunami would reach the cities located on the western coast of Java 35–45 min after the onset of collapse, with a maximum amplitude of 1.5 m (Merak, Panimbang) to 3.4 m (Labuhan), then Bandar Lampung (Sumatra) after >1 h, with a maximum amplitude of 0.3 m (Fig. 3). Such an event would likely cause a significant damage around the Sunda Strait due to high population and a concentration of road and industrial infrastructure at the coast. In 1980, a permanent

volcano observatory was established in Pasauran on the western coast of Java, about 50 km east of the Krakatau archipelago. A short-period seismometer placed on the volcano flank, visual control and daily seismic event statistics are used to determine the current alert level, on the basis of which Indonesian authorities decide about preventive measures, sometimes prohibiting tourism around the archipelago (Hoffmann-Rothe et al. 2006). Ground deformation of the volcano is not permanently monitored. A rapid detection of volcano instability by the observatory together with an alert system on the coast could prevent a hypothetical tsunami from being deadly. Although the hazard is clear, some comfort comes from the tsunami preparedness programme that was initiated in 2006 by the UNESCO and the Indonesian Institute of Sciences (LIPI). As a result, tsunami evacuation routes along the Java coast of Sunda Strait are now operational.

5.2 Maluku Islands (Eastern Indonesia)

The last volcanic tsunamis in Maluku Province occurred in 1608, 1673 and 1840, but these events are briefly documented and their causes remain uncertain (Table 1). In July 1608, ships of the Dutch Fleet were "run aground on the reef, not by a storm, but by a large tidal wave" (Dutch Letter reported by Soloviev and Go 1974). The age of the first historical eruption of Makian volcano is not well constrained (in or before 1550 AD after GVP database), and the existence of the tsunami itself is uncertain. The islands and coasts of western Halmahera are not as densely populated as Java or Bali, but numerous coastal villages and the historical town and harbour of Ternate ($\sim$100,000 inhabitants) might be affected.

5.3 Sangihe Islands and Sulawesi (Indonesia)

A comparable setting to Maluku is found north of Sulawesi, in the Sangihe Islands. Here, volcanic tsunamis have been relatively frequent in the recent past (Table 1: 6 events since 1856). More than 400 people were killed by the tsunami that occurred at the beginning of the 1871 Ruang eruption, most of them at an island facing the volcano (Tagulandang Island). The tsunami penetrated 180 m inland and rose 25 m above sea level on hillslopes (Soloviev and Go 1974).

The 1856 tsunami generated by pyroclastic flows from Awu volcano had little impact, and most of the victims were killed by the volcanic activity itself. The 1892 low-amplitude tsunami (<1 m) was caused by shock waves of the explosions and was observed at considerable distance from the volcano (Ambon at 900 km, Sumbawa at 1,800 km).

The submarine growth of Banua Wuhu volcano likely represents an additional threat in this region. The edifice is nearly emergent and has breached the surface to form an island several times during the nineteenth and twentieth centuries. Surface expression of the 1919 eruption of Banua Wuhu was limited to a 5-m-high water dome over the volcano (Soloviev and Go 1974), as observed during the 2011 eruption off El Hierro, Canary Islands, which was not tsunamigenic (e.g. Carracedo et al. 2012). This surface displacement is erroneously mentioned as a wave run-up in the NGDC database.

There are no major cities or harbours in this archipelago, and the nearest coasts of Philippines and Borneo are respectively 200 and 850 km from the Sangihe volcanic arc. Manado is the nearest large city (population $\sim$400,000), and it is located 110 km SSW of Ruang volcano and protected by the Bunaken archipelago and Santika peninsula (northwestern Sulawesi). Colo volcano (Una-Una Island) is also poorly documented, but it represents a likely tsunami hazard for the surrounding Gulf of Tomini, between North and

South Sulawesi. Only three eruptions have been recorded in historical time (1898, 1938 and 1983: GVP database). Apparently, the large pyroclastic flows that formed during the 1983 VEI 4 eruption did not generate tsunami (Katili and Sudradjat 1984). All coastal cities of Tomini Gulf are located 30–170 km from the volcano.

5.4 Banda Sea (Eastern Indonesia)

Many volcanic islands in the Banda Sea could be included in a list of potentially tsunamigenic volcanoes (e.g. Teon, Nila). Unfortunately, very little data on past eruptions are available. Most of these islands are located in remote areas with low population density. Considering the great distances between these volcanoes and the main islands (>190 km from East Timor, >230 km from Maluku), the only scenario that could present a regional impact is a major debris avalanche (such as the 1888 collapse of Ritter Island in Papua New Guinea). However, given the likelihood of future increases in coastal infrastructure associated with economic development (e.g. fisheries, logging and mineral and oil exploration/exploitation), the regional risk must be evaluated. Banda Api can be considered as an exception because it is the most active volcano of Banda Sea and it is also the closest volcano to Seram and Ambon islands (<200 km). It is a Stromboli-like cone nested in a 7-km-wide caldera. Explosive eruptions up to VEI 3 have occurred during historical times (e.g. 1983, last eruption), but no tsunamis were reported (van Padang 1951; Casadevall et al. 1989).

5.5 Lesser Sunda Islands (Indonesia)

In the Lesser Sunda Islands, Batu Tara is very similar to Banda Api volcano although it is located only 50 km north of the northern coast of Lembata Island (which has no major cities and very low population density). The history of the volcano is not well documented. An explosive eruption occurred in 1847, and the volcano was almost perpetually active between January 2007 and October 2010 (GVP database).

On Lembata Island, the south-eastern flank of Iliwerung stratovolcano was particularly unstable during the 1970s and a landslide tsunami killed more than 539 people in 1979 (Soloviev et al. 1992; Lassa 2009). Since 1973, all eruptions have occurred from the Hobal submarine vent. Iliwerung volcano is located in a remote area, but a large collapse of this steep-flanked edifice might impact the northern coast of Timor (Pante Macassar city has a population of around 5,000).

Paluweh Island represents a tsunami hazard for the northern coast of neighbouring Flores. In 1928, a lava-dome emplacement was accompanied by a landslide and a tsunami that killed 128 people (Table 1). Pyroclastic flows produced during the 1963, 1981 and 2012 eruptions reached the sea and formed pyroclastic deltas on the southern coast facing Flores. Many villages and small cities are located less than 50 km from this volcanic island.

Finally, one of the most active edifices of the Lesser Sunda Arc is the volcanic island of Sangeang Api. No volcanic or landslide tsunamis were reported during the last four centuries, but the active vents are located less than 5 km from the shore and the southern and south-western pyroclastic fans reach the shoreline (Fig. 4). Here, any large pyroclastic flows or debris avalanches could generate waves of enough amplitude to damage the coastal lowlands of eastern Sumbawa and western Flores islands, and especially the cities and harbours of Sape (Sumbawa) and Labuhanbajo (Flores), and Komodo National Park, all located less than 100 km from the volcano.

5.6 Taal caldera lake (Philippines)

In the Philippines, a volcano of concern in terms of tsunami is Taal (Luzon). All historical eruptions of Taal volcano occurred on the 5-km-wide active island located at the centre of the caldera lake (Fig. 5). These eruptions are characterised by phreatic and phreatomagmatic explosions from small cones and tuff-rings, occasionally generating surges and pyroclastic flows to the lake (e.g. 1965, 1911, 1754 and 1749 VEI 4 eruptions). Eruptive centre of the 1716 was located offshore and tsunamis were probably generated by underwater explosions (Maso and Saderra 1904, 1911). The 1965 tsunamigenic eruption is well documented (Moore et al. 1966) and may serve as a type event for tsunami hazard assessment on the coasts of Taal caldera lake. In addition to explosions, lakeside landslides may also produce tsunamis (Ramos 2002). The volcano is permanently monitored by PHIVOLCS (Philippine Institute of Volcanology and Seismology) observatory in Talisay, located 10 km north of the island. A seiche hazard map was established on the basis of observations of the 1754, 1911 and 1965 eruptions (http://volcano.phivolcs.dost.gov.ph/update_VMEPD/vmepd/vmepd/taalhazmaps.htm). The seiche inundation zone covers almost the entire lakeshore and extends up to 3 km inland in Balete (east shore) or Laurel (north-west shore). In such an enclosed basin, tsunamis are referred to as the initial wave

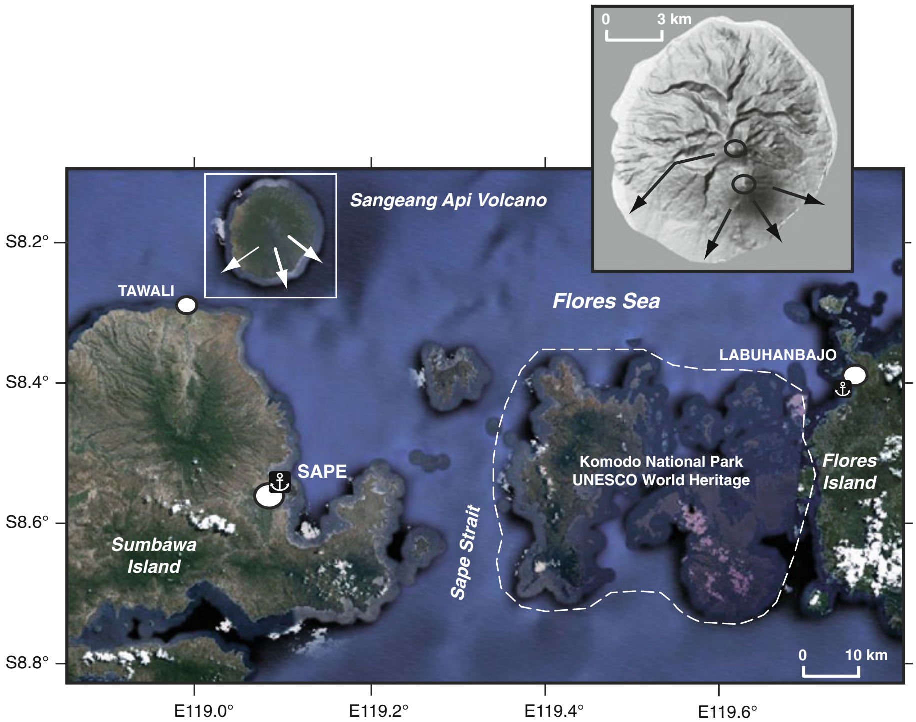

Fig. 4 Satellite image of Sape Strait, between Sumbawa and Flores islands, Lesser Sunda, Indonesia. Sangeang active volcano represents a threat for harbours of Sape and Labuhanbajo, as well as Komodo National Park, in the event of large pyroclastic flows or debris avalanche. Arrows indicate the main paths of historical pyroclastic flows, and black circles the two active vents, Doro Api and Doro Mantoi (sketch map with SRTM relief)

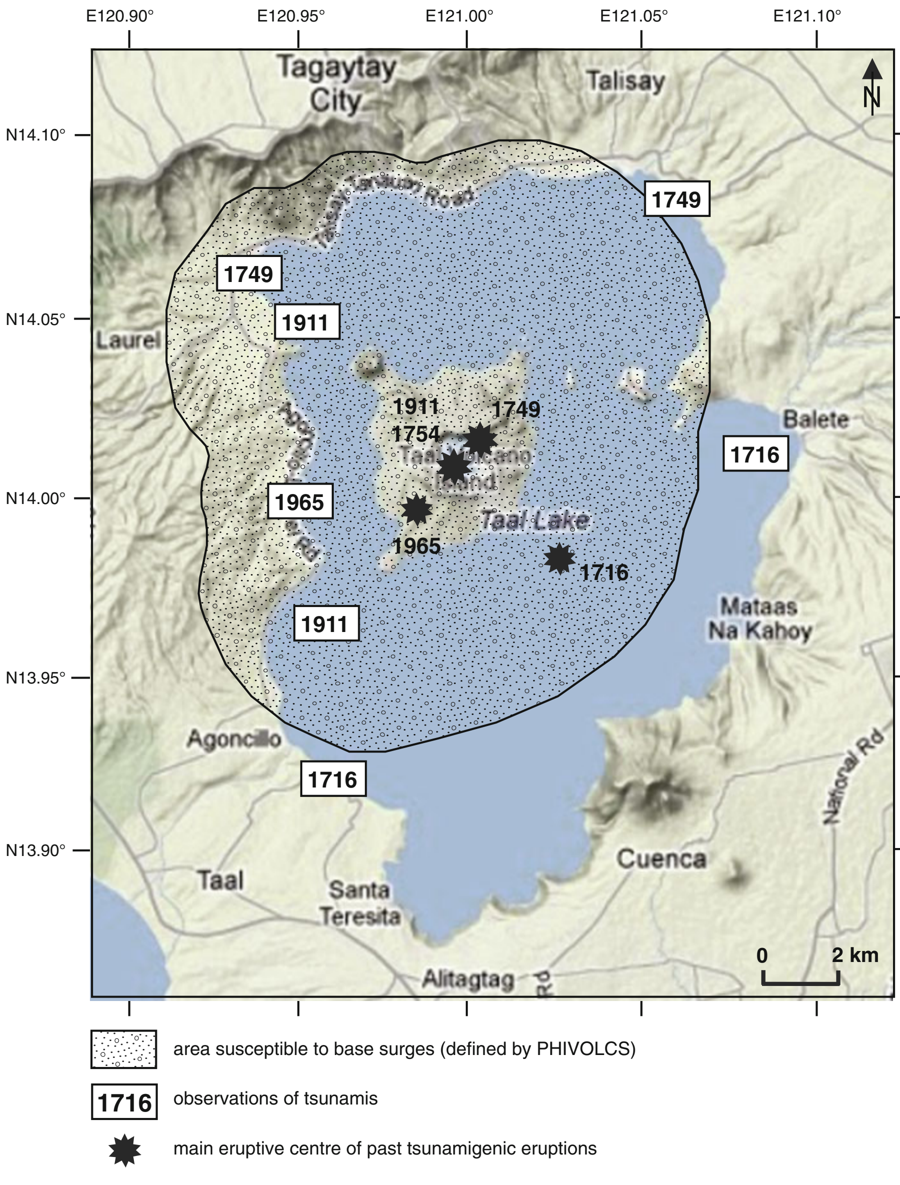

Fig. 5 Shaded relief view of Taal Lake, Luzon, Philippines (SRTM), showing the location of the main eruptive centres of past tsunamigenic eruptions and observations of tsunamis

and the seiche as the harmonic resonance within the lake (Ichinose et al. 2000; Freundt et al. 2007). We thus prefer using the term "tsunami" rather than "seiche".

5.7 Babuyan Archipelago (Northern Philippines)

Other volcanoes in the Philippines that are potentially tsunamigenic include Didicas and Babuyan (Babuyan Archipelago, north of Luzon). Didicas volcano was a submarine edifice

prior to the 1952 eruption. It was then active in 1969 and 1978 (GVP database). Three fishermen were killed during the 1969 eruption, but the cause of their death is unknown (tsunami or pyroclastic surge?). Activity from Didicas is poorly documented and it is not monitored (as far as we know). The two stratovolcanoes composing Babuyan Island, Babuyan Claro (or Mount Pangasun) and Smith (or Mount Babuyan), have both been active during historical times and may represent a tsunami hazard in case of large pyroclastic flows or debris avalanche. The 1831 VEI 4 eruption was the largest of historical time (van Padang 1953). Today, these volcanoes are not monitored permanently, but PHIVOLCS emergency teams are organised in case of increasing seismic activity (e.g. July 1993, February 2004).

5.8 Bismarck Sea (Papua New Guinea)

There are of many volcanic islands and coastal volcanoes in the Bismarck Sea (Papua New Guinea), but most of them are in remote areas. Since the 1888 devastating tsunami, the volcanic activity of Ritter has been offshore, nested in the collapse's scar approximately 700 m west of the island. Low-amplitude tsunamis interpreted as the result of submarine explosions were reported in October 1972 and October 1974 (Cooke 1981). The 1974 tsunami run-up was 0.5 m high in Sakar and Umboi islands, located 10 km from Ritter Island (Cooke 1981; Soloviev et al. 1992). On 19 May 2007, more than 1,500 people on Umboi moved to higher ground after a tsunami destroyed a boat and 4 houses (GVP database). Surprisingly, this event is not reported in the NGDC database. Reports received by Rabaul Volcano Observatory (RVO) indicated evidences of high waves around Ritter Island (GVP database).

Further west, Manam is one of Papua New Guinea's most frequently active volcanoes. Pyroclastic flows have reached the sea many times during the last four centuries (1919, 1956, 1974 and 2004), but no tsunamis were reported. Also frequently active, Bam volcano is steep-flanked and shows evidences of past flank instability (Silver et al. 2009). The density of population around the Bismarck Sea is not high, but a recent increase in coastal infrastructure and development highlights the need for a complete assessment of tsunami hazards including volcanic activity and instability.

5.9 Rabaul (Papua New Guinea)

Rabaul (Eastern New Britain) is a large 8 × 14 km low-lying caldera with two active vents: Tavurvur and Vulcan. Rabaul belongs to the Bismarck volcanic arc from the geological perspective, but the morphology of the Bay of Rabaul, which is opened to the east, does not favour tsunami propagation westward to Bismarck Sea. The city of Rabaul was heavily damaged by the 1994 and subsequent eruptions and has been largely relocated to Kokopo on the SW side of the caldera. Volcanic tsunamis happened here during the 1937 eruption (Arculus and Johnson 1981; Johnson and Threlfald 1985) and again in 1994 (Blong and McKee 1995). In Rabaul, two source mechanisms of tsunamis are identified: (1) pyroclastic flows and base surges and (2) submarine explosions at shallow depths. The first tsunami observed and registered by a tide gauge in 1994 was associated with an earthquake 1 day before the eruption (Blong and McKee 1995). Subsequent tsunamis were associated with the climactic stage of the eruption (Nishimura et al. 2005). The spatial distribution of the run-ups (up to 8 m) suggests that pyroclastic flows and base surges from Vulcan volcano were the main source of the tsunamis (Figs. 6, 7).

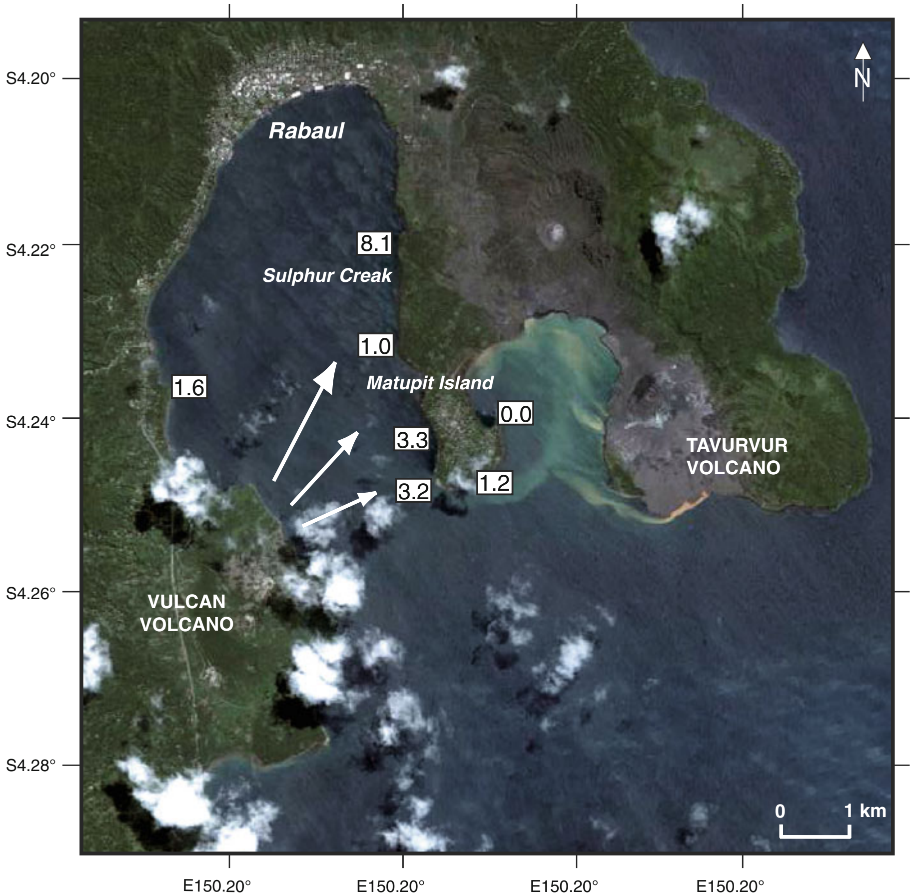

Fig. 6 September 2006 satellite imagery showing the maximum tsunami run-up heights (m a.s.l.) generated by the 1994 Rabaul eruption, Papua New Guinea (modified after Nishimura et al. 2005)

6 Preparing for the next volcanic tsunamis

Existing tsunami warning systems are structured primarily to deal with earthquake-generated tsunamis (e.g. Ina-TEWS: Indonesia Tsunami Early Warning System). These systems rely on automatic processing of earthquake hypocentre, detection of tsunami waves by a network of DART buoys (Deep-ocean Assessment and Reporting of Tsunamis), database of simulated scenarios of tsunami propagation and inundation and a communication infrastructure to issue timely alarms. In Indonesia, Ina-TEWS is held by the BMKG (*Badan Meteorologi, Klimatologi, dan Geofisica*), in collaboration with the LIPI (*Lembaga Ilmu Pengetahuan Indonesia*—Indonesia Institute of Science) and the ITB (*Institut Teknologi Bandung*) for earthquake source prediction and the BPDP (*Balai Pengkajian Dinamika Pantai*—Coastal Dynamics Research Center) of the BPPT (*Badan Pengkajian dan Penerapan Teknologi*—Agency for the Assessment and Application of Technology) for tsunami propagation and run-up prediction.

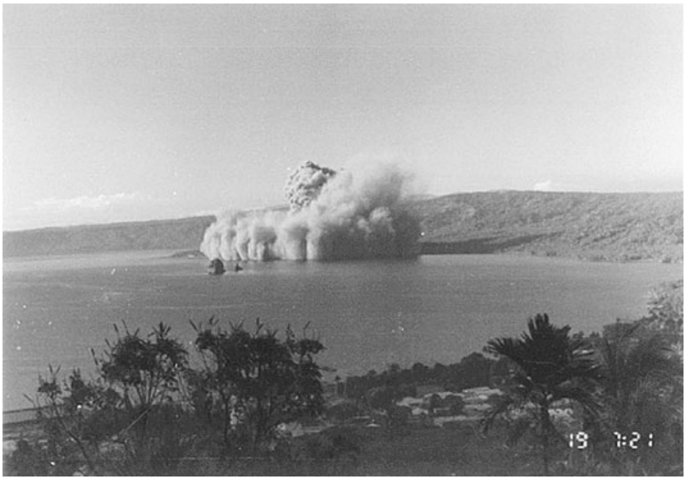

Fig. 7 19 September 1994 pyroclastic flow entering seawater on the northern flank of Vulcan (photograph taken from the Rabaul Volcano Observatory). Note that no water disturbance is apparent yet

Tsunamis happening during a volcanic eruption are sometimes numerous (e.g. Gamkonora 1673, Krakatau 1883, Rabaul 1994) and, using current knowledge, unpredictable. They are characterised by short-period waves and greater dispersion compared to earthquake-generated tsunamis. Thus, instrumental systems are inherently unsuited to dealing with volcanic tsunamis, because hazard is concentrated close to the volcano. With the exceptions of the 1888 Ritter Island and 1883 Krakatau tsunamis, 100 % of the victims of volcanic tsunamis in Southeast Asia were less than 20 km from the volcano (Table 1). Travel time of the waves from the volcano to a distance of 20 km is typically less than 15 min (e.g. Smith and Shepherd 1995; Waythomas and Watts 2003; Torsvik et al. 2010; Maeno and Imamura 2007, 2011; Giachetti et al. 2012).

In this setting, priority is to improve population's preparedness around highlighted volcanoes (see Sect. 5). Key preparedness measures are self-warning and communication. Populations must be educated to the possible warning signs of a volcanic tsunami (explosions offshore, increasing travel distance of pyroclastic flows, rock falls, water oscillations or withdrawal at the shoreline) and able to evacuate in response to their own observations. A permanent monitoring of volcanic activity would allow tsunami alarms to be issued timely by sirens and transmitted as fast as possible to other networks (radio, SMS, RSS, TV, etc.). It would be also appropriate to implement maritime exclusion zones. Such a communication infrastructure does not exist for most of the volcanoes mentioned in this study. Developing such a warning system in Indonesia would necessitate the cooperation of three agencies: BMKG for integration in the Ina-TEWS, PVMBG (*Pusat Vulcanologi dan Mitigasi Bencana Geologi*—Center of Volcanology and Geological Hazard Mitigation) for volcano monitoring and BNPB (*Badan Nasional Penanggulangan Bencana*—National Disaster Management Agency) for evacuation planning and population preparedness.

Developing a more coherent understanding of volcanic tsunami hazard is also grounded on longer-term scientific advances that emphasise different tasks: better characterising the source mechanisms (physical approach), completing regional catalogues of past tsunamis (archives, sedimentary evidences), improving the quality of bathymetric charts in shallow

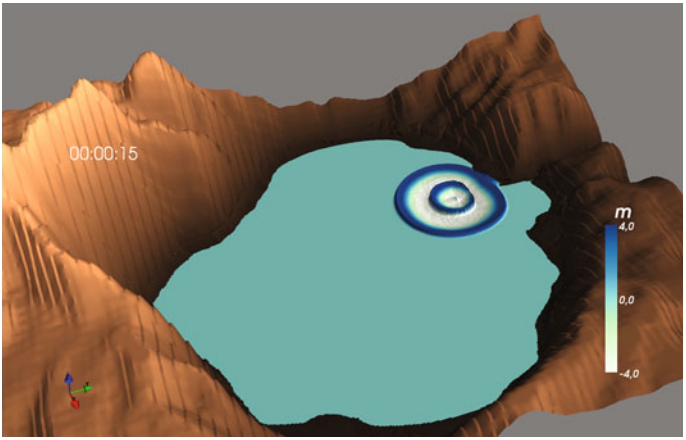

Fig. 8 Simulation of a tsunami generated by underwater explosion in a lake. Initial surface displacement is 80 m and corresponds to explosion energy of 2.1 E^{14} J (M. Ulvrova, *work in progress*). Elevation is exaggerated 5 times

waters, testing different scenarios through numerical simulations (Fig. 8), increasing the density and accuracy of ground deformation monitoring (e.g. geodetic surveys, GPS, tiltmeters, strainmeters, InSAR, photogrammetry), coupling data sets into GIS (Geographic Information System).

7 Conclusion

There is an obvious need to assess volcanic tsunami hazard in Southeast Asia, where rapidly growing population and economy often cohabit with potentially tsunamigenic volcanoes. To adequately plan, manage and develop future coastal development and policy, it is necessary to understand regional hazard and to review and complete available catalogues of past events. Scientific investigation of the hazard itself can always be improved and deliver reliable numerical simulations, hazard maps, estimation of fatalities and costs, etc., but it has to be coupled with a policy of population preparedness and a collaboration between agencies implied in both coastal and volcano hazards.

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