PHILOSOPHICAL TRANSACTIONS A

rsta.royalsocietypublishing.org

Review

Cite this article: Paris R. 2015 Source mechanisms of volcanic tsunamis. *Phil. Trans. R. Soc. A* **373**: 20140380.
http://dx.doi.org/10.1098/rsta.2014.0380

Accepted: 29 July 2015

One contribution of 14 to a theme issue 'Tsunamis: bridging science, engineering and society'.

Subject Areas:
volcanology, geology

Keywords:
volcanic tsunami, flank instability, pyroclastic flows, caldera collapse, underwater explosions

Author for correspondence:
Raphaël Paris
e-mail: r.paris@opgc.univ-bpclermont.fr

THE ROYAL SOCIETY
PUBLISHING

Source mechanisms of volcanic tsunamis

Raphaël Paris[1,2]

[1]Clermont Université, Université Blaise Pascal, BP 10448, 63000 Clermont-Ferrand, France
[2]CNRS, UMR 6524, Magmas et Volcans, 63038 Clermont-Ferrand, France

Volcanic tsunamis are generated by a variety of mechanisms, including volcano-tectonic earthquakes, slope instabilities, pyroclastic flows, underwater explosions, shock waves and caldera collapse. In this review, we focus on the lessons that can be learnt from past events and address the influence of parameters such as volume flux of mass flows, explosion energy or duration of caldera collapse on tsunami generation. The diversity of waves in terms of amplitude, period, form, dispersion, etc. poses difficulties for integration and harmonization of sources to be used for numerical models and probabilistic tsunami hazard maps. In many cases, monitoring and warning of volcanic tsunamis remain challenging (further technical and scientific developments being necessary) and must be coupled with policies of population preparedness.

1. Introduction

Tsunami warning systems are structured primarily to deal with earthquake-generated tsunamis, and rely on automatic processing of earthquake location, wave detection (using buoys or satellites), numerical simulations of wave propagation and inundation, and communication networks to issue timely alarms (e.g. [1]). These systems are not suited to deal with other sources of tsunamis, such as landslides and volcanic eruptions. Harmonizing and integrating all kinds of tsunami sources in a probabilistic analysis of tsunami hazard and warning systems is challenging, as it requires different mechanisms of wave generation and different monitoring techniques to be combined [2–6].

Tsunamis related to volcanic activity and flank instability are characterized by short-period waves, greater dispersion and limited far-field effects compared with earthquake-generated tsunamis (e.g. [7–10]). With the exceptions of the 1888 Ritter Island and 1883

Krakatau tsunamis, all victims of volcanic tsunamis in Southeast Asia were less than 20 km from the volcano [6]. Volcanic tsunamis are not anecdotal phenomena, because they expand the potential damage area of many submarine and coastal volcanoes (including areas not affected by primary volcanic hazards). If not exposed to earthquakes, coastal communities living close to active volcanoes are not necessarily prepared for tsunamis.

Owing to the duration and succession of different stages of volcanic activity, tsunamis during volcanic crises can be numerous and related to different source mechanisms. However, volcanic tsunamis are difficult to predict and to monitor, and the time available for issuing an alarm is often very short, typically a few minutes [4,11–13]. Most volcanic eruptions happening near the coast are fortunately not tsunamigenic, but, when they are, the cause itself of the tsunami is sometimes uncertain and observations are rare or difficult to interpret (e.g. 1650 Kolumbo tsunami in the Aegean Sea [14,15]).

Here we consider volcanic tsunamis *s.l.* to be all tsunamis generated by eruptive processes, rapid ground deformation and slope instability at volcanoes. Different mechanisms might be implied in the generation of volcanic tsunamis [6,7,16,17]: underwater explosion, pyroclastic flow and lahar entering the water, slope instabilities (from rock falls to debris avalanche, including collapse of the coastal lava bench), caldera collapse (resulting in rapid subsidence of the sea floor), volcanic earthquake and shock waves produced by the large explosion.

2. Volcanic earthquakes

Earthquakes preceding or occurring during volcanic eruptions are held liable for 20% of listed volcanic tsunamis [7,16]. Examples are poorly documented and other source mechanisms might be implied in tsunami generation: for example, the 1329 tsunami on the coast of the Etna volcano; the 1827 tsunami in Avacha Bay, Kamchatka (Avachinsky volcano); the 1857 tsunami in Papua New Guinea (Umboi volcano); the 1914 tsunami in Sakurajima Bay, Japan; and the 1916 tsunami at Stromboli. Owing to the lack of instrumental records, the patterns of these earthquakes are not defined, thus making difficult the distinction between volcano-tectonic and pure tectonic events. Among all kinds of earthquakes related to volcanic and magmatic processes, only volcano-tectonic (high-frequency) earthquakes can involve ground deformation large enough to generate a tsunami. Volcano-tectonic earthquakes result from the accumulation of stress induced by magma ascent. They are characterized by seismic swarms at shallow depth (less than 10 km), with magnitudes typically less than $M_s = 6$, and thus generate small-magnitude tsunamis [7,16]. They are often one of the earliest precursors to eruption (e.g. [18,19]). Tsunamis reported in Rabaul Bay (Papua New Guinea) in 1878 and 1937 occurred after the initial earthquake and before the eruption started [20].

Finally, earthquakes, whatever their origin, can trigger slope instabilities and thus indirectly generate tsunamis. The case study of the Kilauea volcano is particularly relevant, with recurrent earthquakes of magnitude $M > 6$ on large thrust faults at the base of the volcanic edifice [21]. The inferred mechanism of the 1975 Kalapana tsunami is a large-scale slumping of the southern submarine flank of Kilauea, following the $M_s = 7.2$ earthquake [22].

3. Slope instabilities

The role of earthquakes in a volcanic setting is also illustrated by the 1792 debris avalanche of Mount Mayuyama (Kyushu Island, Japan) and related tsunami in the Ariake Bay. Mount Mayuyama is a peripheral dome of Unzen volcano, which was active, but the $340 \times 10^6\,m^3$ failure was probably triggered by a strong earthquake [23]. The failure pore fluid pressurization may have contributed to the development of the collapse structure [24]. Tsunami run-ups ranged between 8 and 24 m on the opposite side of the Ariake Bay and 15 030 people were killed [25].

Volcano flanks display a broad variety of instabilities, from rock falls and small landslides (less than $10^6\,m^3$) to large debris avalanches (up to the order of $10^2\,km^3$). Slope instability at

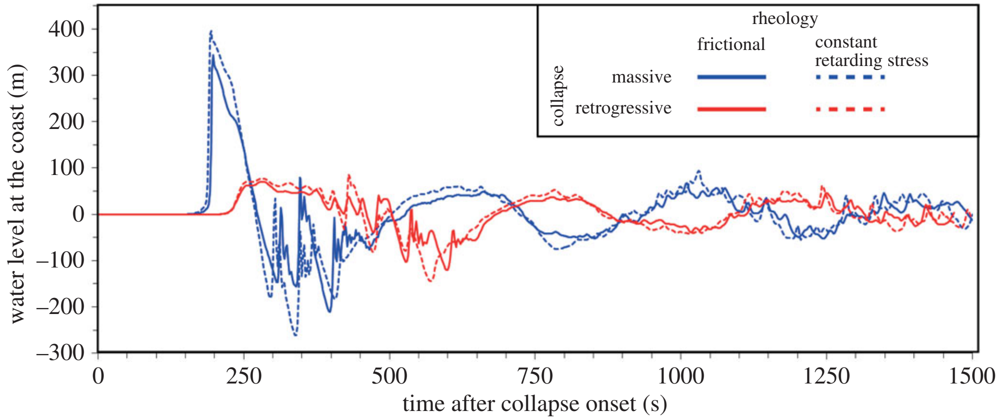

Figure 1. Simulated wave profiles of tsunamis generated by volcano flank failure (Fogo, Cape Verde). Two rheologies (frictional and constant retarding stress) and two scenarios of collapse (massive or retrogressive) are tested. The rheology has a minor effect compared with the failure mechanism (modified after [65]). (Online version in colour.)

volcanoes is not always associated with eruptive phases, as volcanic edifices are by their nature unstable due to structural discontinuities, hydrothermal alteration, magmatic intrusions and high lava accumulation rates (e.g. [26–29]). Tsunamis generated by volcano flank failures represent a low frequency (1% of tsunamis observed during the last four centuries) but potentially high magnitude hazard at the local scale [28].

The entrance of a mass flow in water generates an impulsive wave which then propagates away from the source [9,10,30,31]. The characteristics of tsunamis generated by landslides depend upon their volume, origin (subaerial or submerged) and dynamics (e.g. initial acceleration, maximum velocity, retrogressive behaviour, deformation) (e.g. [32]). In theory, landslide-induced tsunamis might equal or even exceed earthquake-induced tsunamis in terms of energy, but radial spreading limits their propagation. Landslides with rapid deceleration or acceleration generate short-length tsunamis and their far-field propagation is particularly limited by dispersion [33]. As the total length is mostly determined by the length of the landslide, the effect of dispersion is limited in the case of subcritical, large or deformable flows. Water depth is also an important parameter, especially in the open ocean where the height of the leading wave is limited by water depth (e.g. [34]). Collapse of lava benches in deep water often generates very local tsunamis along the southern coast of the Kilauea volcano, Hawaii (e.g. July 1994 [35]).

The most recent damaging tsunami related to volcano instability occurred in December 2002 at the Stromboli volcano [36,37]. The first and larger failure ($17 \times 10^6\ m^3$) involved both submarine and subaerial material, and it was followed by a second failure upslope ($5 \times 10^6\ m^3$) in the Sciara del Fuoco. Both failures produced a local tsunami with a maximum run-up of 8 m along the coast of Stromboli, but had a limited effect on the coast at a distance of more than 200 km from the volcano [38]. Stromboli is one of the most tsunamigenic volcanoes in the world, with five tsunamis observed during the twentieth century (1916, 1919, 1930, 1944 and 1954; [39]). The 1930 tsunami followed violent explosions and rock avalanches in the Sciara del Fuoco and killed two people. Waves of 2–3 m were observed on the coasts of Capo Vaticano, Calabria [38,39]. The recurrent instability of the Stromboli volcano is also confirmed by geological and geophysical data. Four large-scale failures affected the northwestern flank of the volcano during the last 13 ka [40], thus contributing to the formation of a 12 km^3 debris fan offshore [41]. A similar debris avalanche–turbidite system was evidenced on the eastern flanks of Stromboli [42]. It is worth noting that other Italian volcanoes such as Etna, Vesuvius and Ischia were the source of submarine debris avalanches that were likely tsunamigenic [43–45].

Tsunamis caused by volcano instability are also frequent in the Southeast Asia region, where there is a high density of volcanoes in close proximity to the seas [6]. Two examples particularly

(a)

(b)

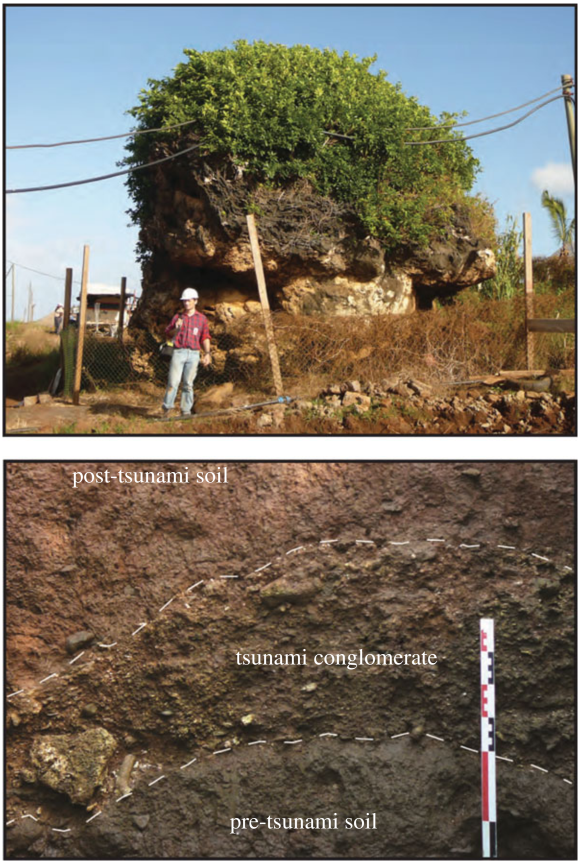

Figure 2. (*a*) Sedimentary evidence of tsunamis on the southern coast of Mauritius Island, Indian Ocean: marine conglomerate dated 4425 $\pm$ 35 BP (^{14}C on coral) and more than 100 tons of coral boulder (adapted from [67]). (*b*) The source of the tsunami is most probably a flank failure of the Piton de la Fournaise volcano, Réunion Island. The tsunami conglomerate is 30 cm thick. (Online version in colour.)

illustrate that moderate-scale landslides can be locally damaging and deadly. The first example is the 1979 tsunami that killed approximately 900 people on Lembata Island, Indonesia [46,47]. The source of the tsunami was a $50 \times 10^6\,m^3$ landslide on the eastern flank of the Iliwerung volcano, a third of the volume reaching the sea. Tsunami run-ups up to 7–9 m were observed on the neighbouring Labala and Waiteba Bays ([47]; Yudhicara 2012, personal communication). The second example is the poorly documented 1928 tsunami that killed 128 people on the coasts of Paluweh Island and Flores, Indonesia, that was caused by a landslide on the northern coast of Flores [20,48,49]. Three waves 5–10 m high were observed, while the volcano was undergoing an explosive Montserrat-like eruption with progradation of a pyroclastic delta fan on the southwestern coast and formation of a new dome. The paradigm of a landslide as a source for the 1928 Paluweh Island tsunami is not robust, and pyroclastic flow should be considered as well, as occurred during the 1997–2003 eruption of the Montserrat volcano [50].

The volumes implied by these case studies are at least one order of magnitude lower than the largest historical volcano flank failures, such as Mount St Helens in 1980 (2.8 km^3 [51]), Ritter Island in 1888 (5 km^3 [52,53]) and Oshima-Oshima in 1741 (2.4 km^3 [54]). The Ritter Island collapse produced a tsunami in the whole of the Bismarck Sea [52,55]. The waves had a period of 3–4 min and run-ups onshore were as high as 10–15 m on the surrounding islands (Umboi, Sakar), 10 m at Hatzfeldhafen (at 330 km from the volcano) and 5 m at Rabaul (at 500 km). Larger failures—tens to hundreds of km^3—were evidenced on the flanks of oceanic shield volcanoes (e.g. [56–62]). Without observational or instrumental data, it is actually difficult to infer the mechanisms controlling these giant mass failures (e.g. discrete or retrogressive failures), and thus to evaluate tsunami hazards (e.g. [63,64]). Their rheology is also poorly constrained, but it has a minor effect on the characteristics of the tsunami, compared with uncertainties on failure mechanisms (figure 1; [63,65,66]). Marine conglomerates found at unusually high elevations in Hawaii, Cape Verde, Mauritius (figure 2), and the Canary Islands were interpreted as being the result of tsunami waves generated by massive flank failures [65,67–70]. The altitudes of these tsunami deposits and the stratigraphy of the volcaniclastic turbidites offshore suggest that many of these ocean-island collapses are multi-stage [63,64,67].

4. Pyroclastic flows

Pyroclastic flows are hot mixtures of gas and particles generated by volcanic eruptions, particularly in the case of dome collapse and plume collapse. 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 on 12 July 2003 [50]) and the Rabaul 1994 eruption (with a maximum run-up of 8 m in Rabaul Bay [71,72]). The tide gauge of the Rabaul Volcano Observatory recorded two sequences of tsunamis: a first small-amplitude tsunami following the initial earthquake on the morning of 18 September 1994 and a series of tsunamis excited by recurrent pyroclastic flows on 19 September [72].

There is geological evidence of pyroclastic flows entering the water and propagating underwater over distances of up to 20 km [73–75]. Cas & Wright [76] established a typology of scenarios in which pyroclastic flows interact with a body of water. However, mechanisms of interaction between pyroclastic flow and water as well as the conditions required to generate a tsunami remain partly elusive because the scientific community lacks observations of this complex phenomenon, and because experimental as well as theoretical studies are rare [75,77,78]. Watts & Waythomas [79] demonstrated that the most energetic and coherent water waves are produced by the dense, basal debris flow component of the pyroclastic flow. Other phenomena such as steam explosion, flow pressure and shear, and pressure impulse would theoretically generate smaller waves [79,80]. The important parameters controlling the interactions between pyroclastic flows and water bodies are the bulk density of the flow and its preservation or disaggregation underwater, the discharge rate, the angle of incidence and the transport distance from the vent [11,76,81]. Freundt [78] demonstrated that flows with a bulk density near that of water generate waves, whatever their temperature. Decoupling of the dilute cloud from the basal flow and propagation over the water surface was reported for the 1883 Krakatau eruption, where approximately 1000 people were burnt at distances as far as 60 km from the volcano [81]. Extensive pumice rafts at the surface of the water might favour passage of pyroclastic flows across the sea.

The 1883 Krakatau eruption and tsunamis that devastated the coasts of the Sunda Strait are particularly well documented, thanks to hundreds of observations and eyewitness accounts that were collected during and after the disaster [82–84]. The eruptive processes, and the source and time propagation of the tsunamis, have been widely debated on the basis of observations, analysis of near-field pyroclastic deposits, tide and pressure gauge records, and numerical modelling [11,16,73,74,82,85–96]. It is now commonly accepted that pyroclastic flows were the source of tsunamis of increasing magnitude from the afternoon of 26 August to the morning of 27 August 1883, even if other processes were involved during the phases preceding or following the paroxysm (rock falls, landslide, caldera collapse).

5. Underwater explosions

After an underwater explosion and while different jet flows are ejected, the development of a water crater might be initiated, depending on the water depth and energy of the explosion [97]. Subsequent expansion, rise and gravitational collapse of the crater create two successive bores

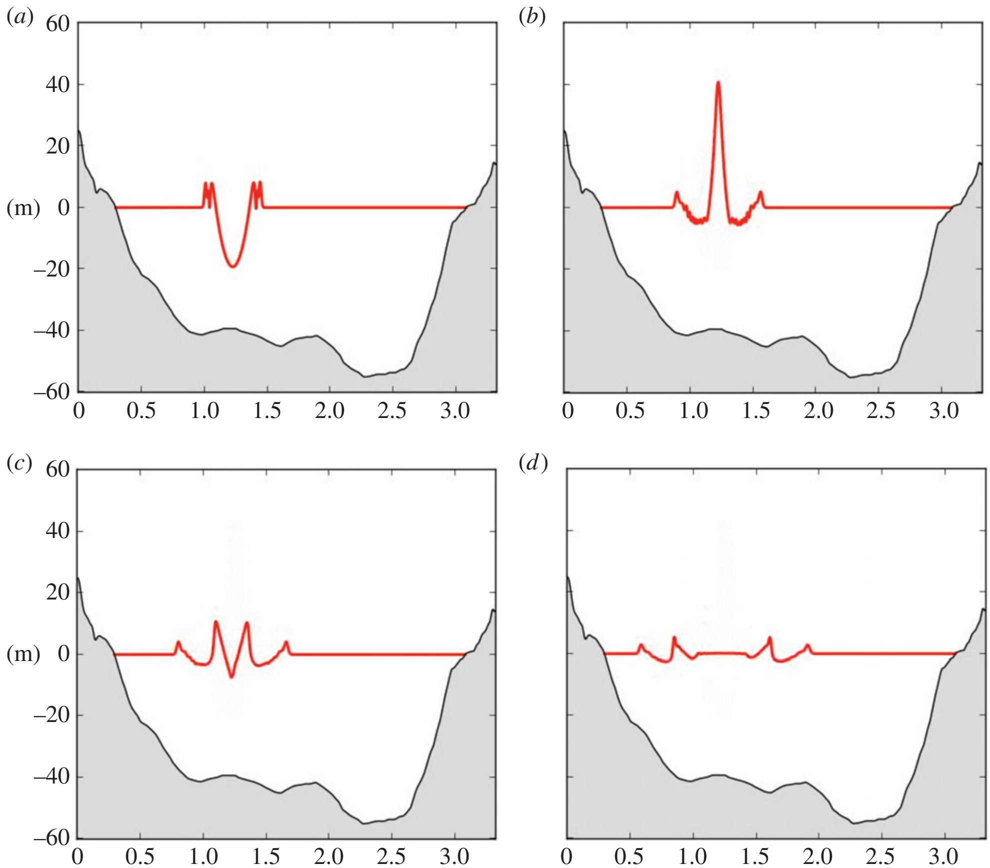

Figure 3. Time series of waves generated by an underwater explosion at Karymsky Lake, Kamchatka (adapted from [12]). (*a*) Explosion and immediate formation of a crater at the water surface; (*b*) rise of a central dome of water while the first bore is propagating radially from the source; (*c*) gravitational collapse of the dome and generation of the second bore; (*d*) propagation of the two successive bores, followed by smaller waves. (Online version in colour.)

followed by a number of smaller undulations propagating radially from the source (figure 3). The theory of waves generated by underwater explosions is well documented [97–101]. The initial surface displacement can be estimated as a function of the explosion energy at a given depth [97], or indirectly after the size of the submerged crater formed by the explosion [102,103].

Waves caused by underwater volcanic explosions during the twentieth century had very small amplitudes [52,85,104,105], excepting the 1996 Karymsky Lake example [106]. Indeed, underwater explosions typically generate waves of short period and great dispersion compared with earthquakes, and the impact in the far-field is often limited. The Myojin-Sho (Japan) submarine eruption in 1952 generated waves less than 1.5 m high at 130 km from the volcano, while a survey vessel of the Japan Hydrographic Department had capsized near the source [107,108]. The precise origin of the disaster was not determined, tsunami or explosion, but consequently an unmanned radio operating survey boat (Manbou) was developed to observe submarine active volcanoes. However, the effect of dispersion is reduced for underwater explosions occurring in shallow-water lakes, as the length-to-depth ratio of the waves rapidly increases and run-up inland can be locally high. This effect was particularly illustrated by the 19 m run-up at Karymsky Lake, Kamchatka, in 1996 [12,106,109].

It is worth noting that many volcanic eruptions starting below the water surface are not tsunamigenic, including Surtseyan-type phreatomagmatic eruptions [12]. Compared with other sources of underwater explosions, magma–water interactions are complex and their physics

(*a*)

(*b*)

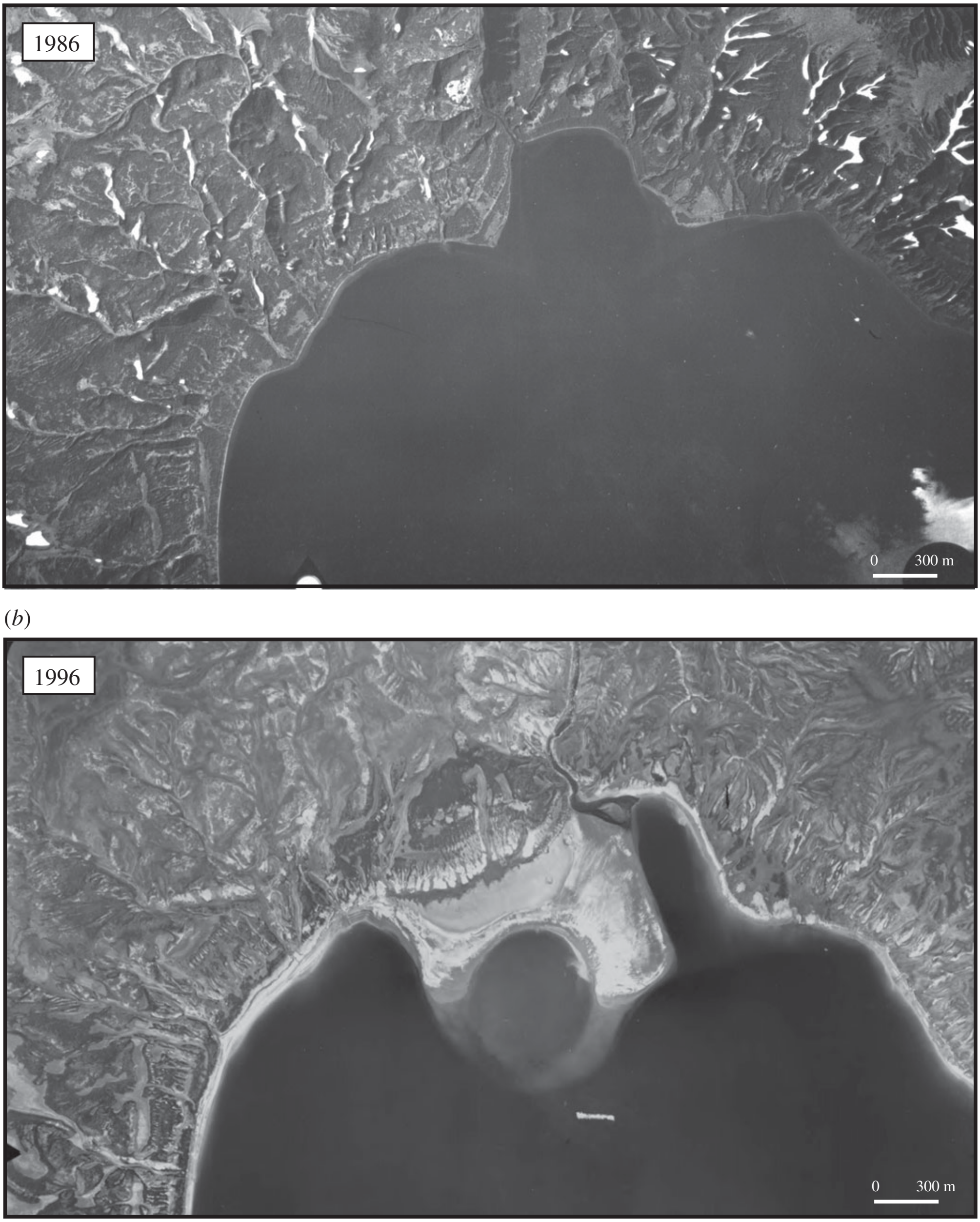

Figure 4. (*a*) 1986 and (*b*) 1996 aerial photographs of the northern part of Karymsky Lake, Akademiya Nauk caldera, Kamchatka (courtesy of A. Belousov and M. Belousova). Note the formation of the tuff ring during the January 1996 eruption and erosion of the shoreline, slopes and riverbeds, both by base surges (close to the tuff ring), lahars (northward, through the Karymsky River) and tsunamis.

is controlled by water depth, geometry of the vent and the magma–water interface, transfer of thermal energy, processes of intermingling and mixing between the magma and the water, metastability of the superheated water and the quantity of gas in the ascending magma [110–112]. Violent steam explosions of eruptions forming maars and tuff rings (Taalian style of [110]) are potentially more tsunamigenic than Surtseyan and other emergent volcanic activities.

Nevertheless, hazards related to underwater volcanic explosions are quite unpredictable and might be underestimated in some cases. Additional hazards come from the triggering of debris

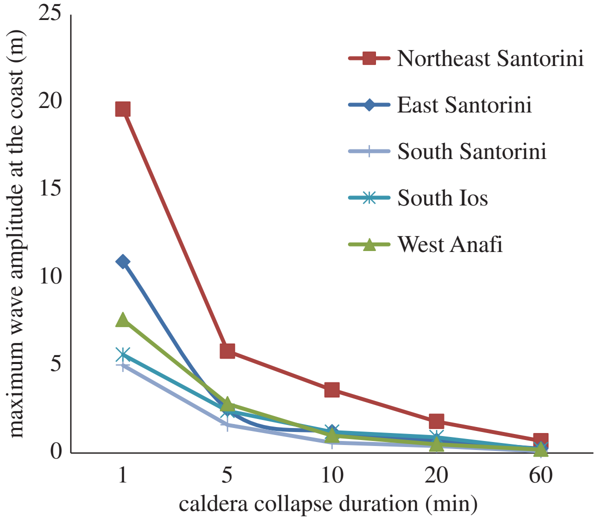

Figure 5. Maximum tsunami wave amplitudes recorded at the coast of Santorini versus duration of the caldera collapse at the Kolumbo submarine volcano, Aegean Sea (modified after [15]). (Online version in colour.)

flows by the outburst of a lake affected by a tsunami, as occurred at Karymsky Lake in 1996 (figure 4; [106]) and Ruapehu in 1995 [113].

6. Shock waves

Long-period sea waves can be produced by phase-coupling with atmospheric compressional gravity or shock waves [114,115]. This rare phenomenon, a so-called meteorological tsunami, requires certain conditions [90]. In the case of volcanic explosion, the explosive pressure must be high enough to excite free waves in the atmosphere, as recorded during the 1956 eruption of the Bezymianny volcano, Kamchatka [20]. The transfer of energy from air to water works only on a deep and long stretch of ocean or sea. This is why coupled air–water waves could explain the worldwide tsunami recorded after the 1883 paroxysmal explosion of Krakatau [90,95], but not the 15–30 m high waves observed in the shallow-water Sunda Strait that were most probably related to pyroclastic flows [11,73]. Volcano-meteorological tsunamis might have been generated by major volcanic explosions in the past, such as the *ca* AD 200 Taupo eruption, New Zealand [116].

7. Caldera collapse

Large explosive eruptions often result in the collapse of the central part of the edifice, thus forming a caldera. The duration of a caldera collapse is poorly constrained (from minutes to hours) and field and experimental studies suggest various geometries and collapse mechanisms [117,118]. In the case of underwater eruption, the collapse generates a subsidence of the water surface that initiates the propagation of a leading trough. The amplitude of the water subsidence depends on the geometry and duration of the collapse [11,94,119], keeping in mind that large collapses lasting a few minutes are theoretically tsunamigenic but probably unrealistic. Incremental collapse of the Fernandina basaltic volcano, Galapagos, consisted of a series of discrete drops over a period of 12 days [120]. Calderas formed during explosive eruptions of silicic magmas are more rapid and en masse. For instance, the bulk volume of the 1991 caldera collapse at Pinatubo, Philippines, might have subsided in 34 min [121]. Ulvrová *et al.* [15] demonstrated that caldera collapse of the Kolumbo submarine volcano, Aegean Sea, would produce significant wave heights (more than 1 m) on the shorelines of Santorini Island if the bulk subsidence lasted less than 10 min (figure 5).

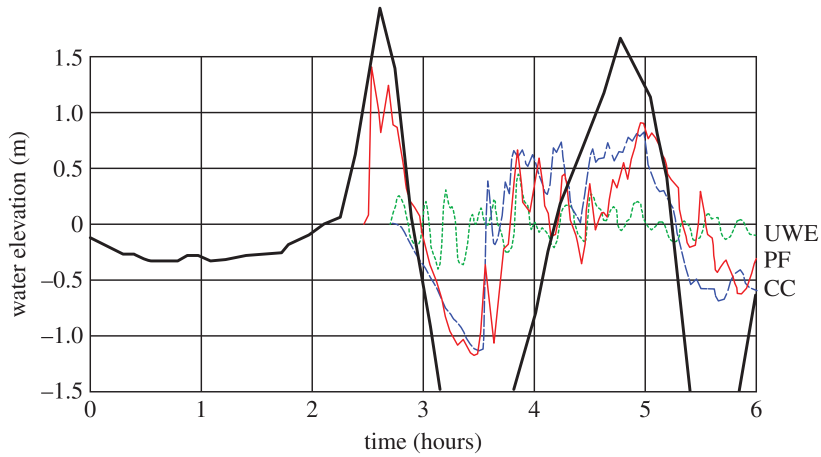

Figure 6. Tsunami waveforms of the 1883 Krakatau tsunami recorded by the Tandjong Priok tide gauge at Batavia-Jakarta (original data filtered by [95]) and numerically simulated [11]. Three scenarios are tested: PF: pyroclastic flow with a volume of 10 km^3 and a volume flux of $1 \times 10^8\ m^3\ s^{-1}$; CC: caldera collapse lasting 30 min; UWE: underwater explosion with an energy of 1×10^{17} joules corresponding to an initial surface displacement of 290 m. (Online version in colour.)

Furthermore, determining the source of tsunamis generated during shallow-water caldera-forming eruptions is often problematic because different tsunamigenic processes might be involved: the caldera collapse itself, but also pyroclastic flows, underwater explosions, earthquakes, slope instabilities and shock waves. High discharge rate eruption of silicic magmas (e.g. rhyolite) during subaqueous caldera-forming eruptions might generate pyroclastic ponds resulting in a dome of water, thus having the opposite effect to caldera subsidence [76]. Controversies over the source of the 1883 Krakatau and 3.6 ka Santorini tsunamis illustrate the complexity of tsunamis associated with caldera-forming eruptions. Maeno & Imamura [11] found that the computed tsunami heights generated by a simulated pyroclastic flow with a volume of more than 5 km^3 and a discharge rate of $10^7\ m^3\ s^{-1}$ are consistent with historical records of the 1883 Krakatau tsunamis in Sunda Strait (figure 6). Other source mechanisms such as underwater explosions and caldera collapse (even if sudden) do not fit with the record of the tide gauge record at Tandjong Priok (Batavia-Jakarta harbour, Java).

8. Conclusion

Volcanic tsunamis are less frequent than their seismic counterparts. They are characterized by short to moderate wavelengths and their impact in the far-field is often limited. However, the local impact is potentially disastrous and major volcanic tsunamis are thought to have participated in cultural transitions during Prehistory and Antiquity (e.g. [122,123]).

Considering the diversity of source mechanisms, prevention of volcanic tsunamis through monitoring is challenging and must be coupled with a policy of population preparedness. In terms of hazard evaluation and warning, the worst-case scenarios are: (i) a Bandai-type debris avalanche (due to phreatic explosion) with no precursors to the onset of the paroxysmal phase [24]; (ii) a Mayuyama-type debris avalanche affecting a peripheral non-active edifice that is not monitored [25]; (iii) a large underwater explosion in a lake bordered by densely populated cities; and (iv) tsunamis caused by activity or instability of submarine volcanoes, which are most of the time not monitored.

Competing interests. We declare we have no competing interests.
Funding. We received no funding for this study.

Acknowledgements. This research is realized in the framework of the ASTARTE collaborative project FP7-ENV2013 6.4-3. We thank the reviewers and editor Costas Synolakis for their helpful comments. This is Laboratory of Excellence ClerVolc contribution no. 171.

References

1. Titov VV, González FI, Bernard EN, Eble MC, Mofjeld HO, Newman JC, Venturato AJ. 2005 Real-time tsunami forecasting: challenges and solutions. *Nat. Hazards* **35**, 41–58. (doi:10.1007/s11069-004-2403-3)
2. Iwasaki SI, Sakata S. 2001 Landslide tsunami generation mechanism and its detection for early tsunami warning. Tsunami research at the end of a critical decade. *Adv. Nat. Technol. Hazards Res.* **18**, 229–241. (doi:10.1007/978-94-017-3618-3_16)
3. Tinti S. 2003 Needs and perspectives of tsunami research in Europe. In *Submarine landslides and tsunamis* (eds AC Yalçiner, EN Pelinovsky, E Okal, CE Synolakis), pp. 9–16. NATO Science Series, vol. 21. Dordrecht, The Netherlands: Springer. (doi:10.1007/978-94-010-0205-9_2)
4. Bellotti G, Di Risio M, De Girolamo P. 2009 Feasibility of tsunami early warning systems for small volcanic islands. *Nat. Hazards Earth Syst. Sci.* **9**, 1911–1919. (doi:10.5194/nhess-9-1911-2009)
5. Grezio A, Sandri L, Marzocchi W, Argnani A, Gasparini P, Selva J. 2012 Probabilistic tsunami hazard assessment for Messina Strait area Sicily, Italy. *Nat. Hazards* **64**, 329–358. (doi:10.1007/s11069-012-0246-x)
6. Paris R, Switzer AD, Belousova M, Belousov A, Ontowirjo B, Whelley PL, Ulvrová M. 2014 Volcanic tsunami: a review of source mechanisms, past events and hazards in Southeast Asia Indonesia, Philippines, Papua New Guinea. *Nat. Hazards* **70**, 447–470. (doi:10.1007/s11069-013-0822-8)
7. Begét JE. 2000 Volcanic tsunamis. In *Encyclopedia of volcanoes* (eds H Sigurdsson, B Houghton, SR McNutt, H Rymer, J Stix), pp. 1005–1013. New York, NY: Academic Press.
8. Okal EA, Synolakis CE. 2004 Source discriminants for nearfield tsunamis. *Geophys. J. Int.* **158**, 899–912. (doi:10.1111/j.1365-246X.2004.02347.x)
9. Harbitz CB, Løvholt F, Pedersen G, Masson DG. 2006 Mechanisms of tsunami generation by submarine landslides: a short review. *Norwegian J. Geol.* **86**, 255–264.
10. Di Risio M, De Girolamo P, Beltrami GM 2011 Forecasting landslide generated tsunamis: a review. In *The tsunami threat—research and technology* (ed. NA Märner). Rijeka, Croatia: Intech.
11. Maeno F, Imamura F. 2011 Tsunami generation by a rapid entrance of pyroclastic flow into the sea during the 1883 Krakatau eruption, Indonesia. *J. Geophys. Res.* **116**, B09205. (doi:10.1029/2011JB008253)
12. Ulvrová M, Paris R, Kelfoun K, Nomikou P. 2014 Numerical simulations of tsunami generated by underwater volcanic explosions at Karymskoye Lake Kamchatka, Russia and Kolumbo volcano Aegean Sea, Greece. *Nat. Hazards Earth Syst. Sci.* **14**, 401–412. (doi:10.5194/nhess-14-401-2014)
13. Giachetti T, Paris R, Kelfoun K, Ontowirjo B. 2012 Tsunami hazard related to a flank collapse of Anak Krakatau volcano, Sunda Strait, Indonesia. *Geol. Soc. Lond. Spec. Public.* **361**, 79–89. (doi:10.1144/SP361.7)
14. Nomikou P, Carey S, Bell K, Papanikolaou D, Bejelou K, Cantner K, Sakellariou D, Perros I. 2014 Tsunami hazard risk of a future volcanic eruption of Kolumbo submarine volcano, NE of Santorini Caldera, Greece. *Nat. Hazards* **72**, 1375–1390. (doi:10.1007/s11069-012-0405-0)
15. Ulvrová M, Paris R, Nomikou P, Kelfoun K, Tappin D. Submitted. Source of the tsunami generated by the 1650 eruption of Kolumbo submarine volcano Aegean Sea, Greece.
16. Latter JN. 1981 Tsunamis of volcanic origin: summary of causes with particular references to Krakatoa, 1883. *Bull. Volcanol.* **443**, 467–490. (doi:10.1007/BF02600578)
17. Kienle J, Kowalik Z, Murty TS. 1987 Tsunamis generated by eruptions from Mount St Augustine Volcano, Alaska. *Science* **236**, 1442–1447. (doi:10.1126/science.236.4807.1442)
18. Lahr JC, Chouet BC, Stephens CD, Power JA, Page RA. 1994 Earthquake classification, location, and error analysis in a volcanic environment: implications for the magmatic system of the 1989–1990 eruptions at Redoubt volcano, Alaska. *J. Volcanol. Geotherm. Res.* **62**, 137–152. (doi:10.1016/0377-0273(94)90031-0)

19. Roman DC, Cashman KV. 2006 The origin of volcano-tectonic earthquake swarms. *Geology* **34**, 457–460. (doi:10.1130/G22269.1)
20. Soloviev SL, Go CN. 1974 *A catalogue of tsunamis on the western shore of the Pacific Ocean*. Moscow, Russia: Academy of Sciences of the USSR, Nauka Publishing House.
21. Ando M. 1979 The Hawaii earthquake of November 29, 1975: low dip angle faulting due to forceful injection of magma. *J. Geophys. Res.* **84**, 7616–7626. (doi:10.1029/JB084iB13p07616)
22. Ma KF, Kanamori H, Satake K. 1999 Mechanism of the 1975 Kalapana, Hawaii, earthquake inferred from tsunami data. *J. Geophys. Res.* **104**, 13 153–13 167. (doi:10.1029/1999JB900073)
23. Michiue M, Hinokidani O, Miyamoto K. 1999 Study on the Mayuyama tsunami disaster in 1792. In *Proc. 28th Congress of the Int. Assoc. for Hydraulic Research, Graz, Austria, 22–27 August 1999*. International Association for Hydro-Environment Engineering and Research, CD-R d141.pdf.
24. Siebert L, Glicken H, Ui T. 1987 Volcanic hazards from Bezymianny and Banda type eruptions. *Bull. Volcanol.* **49**, 435–459. (doi:10.1007/BF01046635)
25. Tsuji Y, Hino T. 1993 Damage and inundation height of the 1792 Shimabara landslide tsunami along the coast of Kumamoto prefecture. *Bull. Earthq. Res. Inst. Univ. Tokyo* **682**, 91–176.
26. Siebert L. 1984 Large volcanic debris avalanches: characteristics of source areas, deposits, and associated eruptions. *J. Volcanol. Geotherm. Res.* **22**, 163–197. (doi:10.1016/0377-0273(84)90002-7)
27. Van Wyk de Vries B, Francis PW. 1997 Catastrophic collapses at stratovolcanoes induced by gradual volcano spreading. *Nature* **387**, 387–390. (doi:10.1038/387387a0)
28. Keating BH, McGuire WJ. 2000 Island edifice failures and associated tsunami hazards. *Pure Appl. Geophys.* **157**, 899–955. (doi:10.1007/s000240050011)
29. Lagmay AMF, van Wyk de Vries B, Kerle N, Pyle DM. 2000 Volcano instability induced by strike-slip faulting. *Bull. Volcanol.* **62**, 331–346. (doi:10.1007/s004450000103)
30. Iwasaki SI. 1997 The wave forms and directivity of a tsunami generated by an earthquake and a landslide. *Sci. Tsunami Hazards* **15**, 23–40.
31. Masson DG, Harbitz CB, Wynn RB, Pedersen G, Løvholt F. 2006 Submarine landslides: processes, triggers and hazard predictions. *Phil. Trans. R. Soc. A* **364**, 2009–2039. (doi:10.1098/rsta.2006.1810)
32. Løvholt F, Pedersen G, Harbitz CB, Glimsdal S, Kim J. 2015 On the characteristics of landslide tsunamis. *Phil. Trans. R. Soc. A* **373**, 20140376. (doi:10.1098/rsta.2014.0376)
33. Haugen KB, Løvholt F, Harbitz CB. 2005 Fundamental mechanisms for tsunami generation by submarine flows in idealised geometries. *Mar. Pet. Geol.* **22**, 209–217. (doi:10.1016/j.marpetgeo.2004.10.016)
34. Synolakis CE. 1987 The runup of solitary waves. *J. Fluid Dyn.* **185**, 523–545.
35. Mattox TN, Mangan MT. 1997 Littoral hydrovolcanic explosions: a case-study of lava-seawater interaction at Kilauea volcano. *J. Volcanol. Geotherm. Res.* **75**, 1–17. (doi:10.1016/S0377-0273(96)00048-0)
36. Bonaccorso A, Calvari S, Garfì L, Lodato L, Patanè D. 2003 Dynamics of the December 2002 flank failure and tsunami at Stromboli volcano inferred by volcanological and geophysical observations. *Geophys. Res. Lett.* **30**, 1941. (doi:10.1029/2003GL017702)
37. Tinti S, Pagnoni G, Zaniboni F. 2006 The landslides and tsunamis of the 30th of December 2002 in Stromboli analysed through numerical simulations. *Bull. Volcanol.* **68**, 462–479. (doi:10.1007/s00445-005-0022-9)
38. Maramai A, Graziani L, Alessio G, Burrato P, Colini L, Cucci L, Nappi R, Nardi A, Vilardo G. 2005 Near- and far-field survey report of the 30 December 2002 Stromboli Southern Italy tsunami. *Mar. Geol.* **215**, 93–106. (doi:10.1016/j.margeo.2004.11.009)
39. Maramai A, Graziani L, Tinti S. 2005 Tsunamis in the Aeolian Islands Southern Italy: a review. *Mar. Geol.* **214**, 11–21. (doi:10.1016/j.margeo.2004.03.018)
40. Tibaldi A. 2001 Multiple sector collapses at Stromboli volcano, Italy: how they work. *Bull. Volcanol.* **63**, 112–125. (doi:10.1007/s004450100129)
41. Romagnoli C, Kokelaar P, Casalbore D, Chiocci FL. 2009 Lateral collapses and active sedimentary processes on the northwestern flank of Stromboli volcano, Italy. *Mar. Geol.* **265**, 101–119. (doi:10.1016/j.margeo.2009.06.013)

42. Romagnoli C, Casalbore D, Chiocci FL, Bosman A. 2009 Offshore evidence of large-scale lateral collapses on the eastern flank of Stromboli, Italy, due to structurally-controlled, bilateral flank instability. *Mar. Geol.* **262**, 1–13. (doi:10.1016/j.margeo.2009.02.004)
43. Pareschi MT, Boschi E, Mazzarini F, Favalli M. 2006 Large submarine landslide offshore Mt. Etna. *Geophys. Res. Lett.* **33**, L13302. (doi:10.1029/2006GL026064)
44. Milia A, Raspini A, Torrente MM. 2007 The dark nature of Somma-Vesuvius volcano: evidence from the ∼3.5 ka B.P. Avellino eruption. *Q. Int.* **173–174**, 57–66. (doi:10.1016/j.quaint.2007.03.001)
45. De Alteriis G, Insinga DD, Morabito S, Morra V, Chiocci FL, Terrasi F, Lubritto C, Di Benedetto C, Pazzanese M. 2010 Age of submarine debris avalanches and tephrostratigraphy offshore Ischia Island, Tyrrhenian Sea, Italy. *Mar. Geol.* **278**, 1–18. (doi:10.1016/j.margeo.2010.08.004)
46. Soloviev SL, Go CN, Kim KS. 1992 *Catalog of tsunamis in Pacific*. New Delhi, India: Academy of Sciences of the USSR, Moscow (transl. by Amerind Publishing Co. Pvt Ltd).
47. Lassa J. 2009 The forgotten disaster? Remembering the Larantuka and Lembata disaster 1979–2009. *J. NTT Stud.* **1**, 159–184. [In Indonesian.]
48. Berninghausen WH. 1969 Tsunamis and seismic seiches of Southeast Asia. *Bull. Seismol. Soc. Amer.* **59**, 289–297.
49. Van Padang MN. 1983 History of the volcanology in the former Netherlands East Indies. *Scrip. Geol.* **71**, 1–76.
50. Pelinovsky E, Zahibo N, Dunkley P, Edmonds M, Herd R, Talipova T, Kozelkov A, Nikolkina I. 2004 Tsunamis generated by the volcano eruption on July 12–13, 2003 at Montserrat, Lesser Antilles. *Sci. Tsunami Hazards* **22**, 44–57.
51. Voight B, Glicken H, Janda RJ, Douglas PM. 1981 Catastrophic rockslide avalanche of May 18. In *The 1980 eruptions of Mount St Helens*, vol. 1250 (eds PW Lipman, DR Mullineaux), pp. 347–378. Washington, DC: U.S. Geological Survey Professional Papers.
52. Cooke RJS. 1981 Eruptive history of the volcano at Ritter Island. *Geol. Surv. Papua New Guinea Memoir* **10**, 115–123.
53. Johnson RW. 1987 Large-scale volcanic cone collapse; the 1888 slope failure of Ritter volcano. *Bull. Volcanol.* **49**, 669–679. (doi:10.1007/BF01080358)
54. Satake K, Kato Y. 2001 The 1741 Oshima-Oshima eruption: extent and volume of submarine debris avalanche. *Geophys. Res. Lett.* **28**, 427–430. (doi:10.1029/2000GL012175)
55. Ward SN, Day S. 2003 Ritter Island volcano—lateral collapse and the tsunami of 1888. *Geophys. J. Int.* **154**, 891–902. (doi:10.1046/j.1365-246X.2003.02016.x)
56. Holcomb RT, Searle RC. 1991 Large landslides from oceanic volcanoes. *Mar. Geotechnol.* **10**, 19–32. (doi:10.1080/10641199109379880)
57. Moore JG, Clague DA, Holcomb RT, Lipman PW, Normark WR, Torresan ME. 1989 Prodigious submarine landslides on the Hawaiian Ridge. *J. Geophys. Res.* **94**, 17 465–17 484. (doi:10.1029/JB094iB12p17465)
58. Oehler JF, Labazuy P, Lénat JF. 2004 Recurrence of major flank landslides during the last 2-Ma-history of Réunion Island. *Bull. Volcanol.* **66**, 585–598. (doi:10.1007/s00445-004-0341-2)
59. Paris R, Pérez Torrado FJ, Carracedo JC. 2005 Massive flank failures and tsunamis in the Canary Islands: past, present, future. *Z. Geomorphol. Suppl. Band* **140**, 37–54.
60. Masson DG, Watts AB, Gee MRJ, Urgeles R, Mitchell NC, Le Bas TP, Canals M. 2002 Slope failures on the flanks of the western Canary Islands. *Earth Sci. Rev.* **57**, 1–35. (doi:10.1016/S0012-8252(01)00069-1)
61. Masson DG, Le Bas TP, Grevemeyer I, Weinrebe W. 2008 Flank collapse and large-scale landsliding in the Cape Verde Islands, off West Africa. *Geochem. Geophys. Geosyst.* **9**. (doi:10.1029/2008GC001983)
62. Mitchell NC. 2003 Susceptibility of mid-ocean ridge volcanic islands and seamounts to large-scale landsliding. *J. Geophys. Res.* **108**, 2397. (doi:10.1029/2002JB001997)
63. Giachetti T, Paris R, Kelfoun K, Pérez Torrado FJ. 2011 Numerical modelling of the tsunami triggered by the Gùimar debris avalanche, Tenerife Canary Islands: comparison with field-based data. *Mar. Geol.* **284**, 189–202. (doi:10.1016/j.margeo.2011.03.018)
64. Hunt JE, Wynn RB, Talling PJ, Masson DG. 2013 Multistage collapse of eight western Canary Island landslides in the last 1.5 Ma: sedimentological and geochemical evidence

from subunits in submarine flow deposits. *Geochem. Geophys. Geosyst.* **14**, 2159–2181. (doi:10.1002/ggge.20138)

65. Paris R, Giachetti T, Chevalier J, Guillou H, Frank N. 2011 Tsunami deposits in Santiago Island Cape Verde archipelago as possible evidence of a massive flank failure of Fogo volcano. *Sedimentary Geol.* **239**, 129–145. (doi:10.1016/j.sedgeo.2011.06.006)
66. Kelfoun K, Giachetti T, Labazuy P. 2010 Landslide-generated tsunamis at Reunion Island. *J. Geophys. Res.* **115**, F04012. (doi:10.1029/2009JF001381)
67. Paris R, Kelfoun K, Giachetti T. 2013 Marine conglomerate and reef megaclasts at Mauritius Island Indian Ocean: evidences of a tsunami generated by a flank collapse of Piton de la Fournaise volcano, Réunion Island? *Sci. Tsunami Hazards* **32**, 281–291.
68. Moore JG, Moore GW. 1984 Deposit from a giant wave on the island of Lanai, Hawaii. *Science* **226**, 1312–1315. (doi:10.1126/science.226.4680.1312)
69. McMurtry GM, Watts P, Fryer GJ, Smith JR, Imamura F. 2004 Giant landslides, mega-tsunamis and paleo-sea level in the Hawaiian Islands. *Mar. Geol.* **203**, 219–233. (doi:10.1016/S0025-3227(03)00306-2)
70. Pérez Torrado FJ, Paris R, Cabrera MC, Schneider JL, Wassmer P, Carracedo JC, Rodriguez Santana A, Santana F. 2006 The Agaete tsunami deposits Gran Canaria: evidence of tsunamis related to flank collapses in the Canary Islands. *Mar. Geol.* **227**, 137–149. (doi:10.1016/j.margeo.2005.11.008)
71. Blong RJ, McKee CO. 1995 *The Rabaul eruption 1994—destruction of a town*. Sydney, Australia: Natural Hazards Research Center, Macquarie University.
72. Nishimura Y, Nakagawa M, Kuduon J, Wukawa J. 2005 Timing and scale of tsunamis caused by the 1994 Rabaul eruption, East New Britain, Papua New Guinea. In *Tsunamis: case studies and recent developments* (ed. K Satake), pp. 43–56. Berlin, Germany: Springer.
73. Carey S, Sigurdsson H, Mandeville C, Bronto S. 1996 Pyroclastic flows and surges over water: an example from the 1883 Krakatau eruption. *Bull. Volcanol.* **57**, 493–511. (doi:10.1007/BF00304435)
74. Mandeville CW, Carey S, Sigurdsson H. 1996 Sedimentology of the Krakatau 1883 submarine pyroclastic deposits. *Bull. Volcanol.* **57**, 512–529. (doi:10.1007/BF00304436)
75. Allen SR, Freundt A, Kurokawa K. 2011 Characteristics of submarine pumice-rich density current deposits sources from turbulent mixing of subaerial pyroclastic flow at the shoreline: field and experimental assessment. *Bull. Volcanol.* **74**, 657–675. (doi:10.1007/s00445-011-0553-1)
76. Cas RAF, Wright JV. 1991 Subaqueous pyroclastic flows and ignimbrites: an assessment. *Bull. Volcanol.* **53**, 357–380. (doi:10.1007/BF00280227)
77. Legros F, Druitt TH. 2000 On the emplacement of ignimbrite in shallow-marine environments. *J. Volcanol. Geotherm. Res.* **95**, 9–22. (doi:10.1016/S0377-0273(99)00116-X)
78. Freundt A. 2003 Entrance of hot pyroclastic flows into the sea: experimental observations. *Bull. Volcanol.* **65**, 144–164.
79. Watts P, Waythomas CF. 2003 Theoretical analysis of tsunami generation by pyroclastic flows. *J. Geophys. Res.* **108**, 2563–2560. (doi:10.1029/2002JB002265)
80. Tinti S, Pagnoni G, Piatanesi A. 2003 Simulations of tsunamis induced by volcanic activity in the Gulf of Naples (Italy). *Nat. Hazards Earth Syst. Sci.* **3**, 311–320. (doi:10.5194/nhess-3-311-2003)
81. Carey S, Sigurdsson H, Mandeville C, Bronto S. 2000 Volcanic hazards from pyroclastic flow discharge into the sea: examples from the 1883 eruption of Krakatau, Indonesia. *Geol. Soc. Amer. Spec. Publ.* **345**, 1–14. (doi:10.1130/0-8137-2345-0.1)
82. Verbeek RM. 1886 *Krakatau*. Batavia, Indonesia: Imprimerie de l'Etat.
83. Symons G. 1888 *The eruption of Krakatau and subsequent phenomena: reports of the Krakatau Committee of the Royal Society*. London, UK: Trubner.
84. Simkin T, Fiske RS. 1983 *Krakatau 1883: the volcanic eruption and its effects*. Washington, DC: Smithsonian Institution Press.
85. Stehn CE. 1929 The geology and volcanism of the Krakatau group. In *Proc. 4th Pacific Science Congress, Batavia, Indonesia, 16–25 May 1929*, pp. 1–55. Rockville, MD: American Society of Plant Biologists.
86. Williams H. 1941 Calderas and their origin. *Univ. Calif. Publ. Geol. Sci.* **25**, 239–346.

87. Press M, Ewing F. 1955 Tide-gage disturbances from the great eruption of Krakatoa. *Trans. Amer. Geophys. Union* **361**, 53–60. (doi:10.1029/TR036i001p00053)
88. Self S, Rampino MR. 1981 The 1883 eruption of Krakatau. *Nature* **294**, 699–704. (doi:10.1038/294699a0)
89. Yokoyama I. 1981 A geophysical interpretation of the 1883 Krakatau eruption. *J. Volcanol. Geotherm. Res.* **9**, 359–378. (doi:10.1016/0377-0273(81)90044-5)
90. Yokoyama I. 1987 A scenario of the 1883 Krakatau tsunami. *J. Volcanol. Geotherm. Res.* **34**, 123–132. (doi:10.1016/0377-0273(87)90097-7)
91. Camus G, Vincent PM. 1983 Discussion of a new hypothesis for the Krakatau volcanic eruption in 1883. *J. Volcanol. Geotherm. Res.* **19**, 167–173. (doi:10.1016/0377-0273(83)90130-0)
92. Francis PW. 1985 The origin of the 1883 Krakatau tsunamis. *J. Volcanol. Geotherm. Res.* **25**, 349–363. (doi:10.1016/0377-0273(85)90021-6)
93. Self S. 1992 Krakatau revisited: the course of events and interpretation of the 1883 eruption. *Geo. J.* **282**, 109–121. (doi:10.1007/bf00177223)
94. Nomanbhoy N, Satake K. 1995 Generation mechanism of tsunamis from the 1883 Krakatau eruption. *Geophys. Res. Lett.* **224**, 509–512. (doi:10.1029/94GL03219)
95. Choi BH, Pelinovsky E, Kim KO, Lee JS. 2003 Simulation of the trans-oceanic tsunami propagation due to the 1883 Krakatau volcanic eruption. *Nat. Hazards Earth Syst. Sci.* **3**, 321–332. (doi:10.5194/nhess-3-321-2003)
96. Paris R, Wassmer P, Lavigne F, Belousov A, Belousova M, Iskandarsyah Y, Benbakkar M, Ontowirjo B, Mazzoni N. 2014 Coupling eruption and tsunami records: the Krakatau 1883 case study, Indonesia. *Bull. Volcanol.* **76**, 814. (doi:10.1007/s00445-014-0814-x)
97. Le Méhauté BL. 1971 Theory of explosion-generated water waves. In *Advances in hydroscience*, vol. 7 (ed. VT Chow), pp. 1–79. New York, NY: Academic Press.
98. Mirchina NR, Pelinovsky EN. 1988 Estimation of underwater eruption energy based on tsunami wave data. *Nat. Hazards* **1**, 277–283. (doi:10.1007/BF00137232)
99. Duffy DG. 1992 On the generation of oceanic surface waves by underwater volcanic explosions. *J. Volcanol. Geotherm. Res.* **50**, 323–344. (doi:10.1016/0377-0273(92)90100-R)
100. LeMéhauté BL, Wang S. 1996 *Water waves generated by underwater explosion*. Advanced Series on Ocean Engineering. River Edge, NJ: World Scientific.
101. Egorov Y. 2007 Tsunami wave generation by the eruption of underwater volcano. *Nat. Hazards Earth Syst. Sci.* **7**, 65–69. (doi:10.5194/nhess-7-65-2007)
102. Sato H, Taniguchi H. 1997 Relationship between crater size and ejecta volume of recent magmatic and phreato-magmatic eruptions: implications for energy partitioning. *Geophys. Res. Lett.* **24**, 205–208. (doi:10.1029/96GL04004)
103. Goto A, Taniguchi H, Yoshida M, Ohba T, Oshima H. 2001 Effects of explosion energy and depth to the formation of blast wave and crater: field explosion experiment for the understanding of volcanic explosion. *Geophys. Res. Lett.* **28**, 4287–4290. (doi:10.1029/2001GL013213)
104. Johnson RW, Tuni D. 1987 Kavachi, an active forearc volcano in the western Solomon Islands: reported eruptions between 1950 and 1982. In *Marine geology, geophysics, and geochemistry of the Woodlark Basin, Solomon Islands* (eds B Taylor, NF Exon), pp. 89–112. Earth Science Series, vol. 7. Reston, VA: Circum-Pacific Council for Energy and Mineral Resources.
105. Smith MS, Shepherd JB. 1993 Preliminary investigations of the tsunami hazard of Kick'em Jenny submarine volcano. *Nat. Hazards* **7**, 257–278. (doi:10.1007/BF00662650)
106. Belousov A, Voight B, Belousova M, Muravyev Y. 2000 Tsunamis generated by underwater volcanic explosions: unique data from 1996 eruption in Karymskoye Lake, Kamchatka, Russia. *Pure Appl. Geophys.* **157**, 1135–1143. (doi:10.1007/s000240050021)
107. Dietz RS, Sheehy MJ. 1954 Transpacific detection of Myojin volcanic explosions by underwater sound. *Bull. Geol. Soc. Amer.* **65**, 941–965. (doi:10.1130/0016-7606(1954)65[941:TDOMVE]2.0.CO;2)
108. Nakano M, Unoki S, Hanzawa M, Marumo R, Fukuoka J. 1954 Oceanographic features of a submarine eruption that destroyed the Kaiyo-Maru No. 5. Sears Foundation. *J. Mar. Res.* **13**, 48–66.
109. Torsvik T, Paris R, Didenkulova I, Pelinovsky E, Belousov A, Belousova M. 2011 Numerical simulation of explosive tsunami wave generation and propagation in Karymskoye Lake, Russia. *Nat. Hazards Earth Syst. Sci.* **1011**, 2359–2369.

110. Kokelaar P. 1986 Magma-water interactions in subaqueous and emergent basaltic volcanism. *Bull. Volcanol.* **48**, 275–289. (doi:10.1007/BF01081756)
111. Wohletz KH. 1986 Explosive magma–water interactions: thermodynamics, explosion mechanisms, and field studies. *Bull. Volcanol.* **48**, 245–2654. (doi:10.1007/BF01081754)
112. Morrissey M, Gisler G, Weaver R, Gittings M. 2010 Numerical model of crater lake eruptions. *Bull. Volcanol.* **72**, 1169–1178. (doi:10.1007/s00445-010-0392-5)
113. Lecointre J, Hodgson K, Neall V, Cronin S. 2004 Lahar-triggering mechanisms and hazard at Ruapehu volcano, New Zealand. *Nat. Hazards* **31**, 85–109. (doi:10.1023/B:NHAZ.0000020256.16645.eb)
114. Ewing M, Press F. 1953 Further study of atmospheric pressure fluctuations recorded on seismographs. *Trans. Am. Geophys. Union* **34**, 95–100. (doi:10.1029/TR034i001p00095)
115. Rabinovich AB, Monserrat S. 1996 Meteorological tsunamis near the Balearic and Kuril islands: descriptive and statistical analysis. *Nat. Hazards* **13**, 55–90. (doi:10.1007/BF00156506)
116. Lowe DJ, De Lange WP. 2000 Volcano-meteorological tsunamis, the c. AD 200 Taupo eruption New Zealand and the possibility of a global tsunami. *Holocene* **10**, 401–407. (doi:10.1191/095968300670392643)
117. Roche O, Druitt TH, Merle O. 2000 Experimental study of caldera formation. *J. Geophys. Res.* **105**, 395–416. (doi:10.1029/1999JB900298)
118. Stix J, Kobayashi T. 2008 Magma dynamics and collapse mechanisms during four historic caldera-forming events. *J. Geophys. Res.* **113**, B09205. (doi:10.1029/2007JB005073)
119. Maeno F, Imamura F, Taniguchi H. 2006 Numerical simulations of tsunamis generated by caldera collapse during the 7.3 ka Kikai eruption, Kyushu, Japan. *Earth Planets Space* **58**, 1013–1024. (doi:10.1186/BF03352606)
120. Simkin T, Howard KA. 1970 Caldera collapse in the Galápagos Islands, 1968. *Science* **169**, 429–437. (doi:10.1126/science.169.3944.429)
121. Scott WE, Hoblitt RP, Torres RC, Self S, Martinez MML, Timoteo Jr N. 1996 Pyroclastic flows of the June 15, 1991, climactic eruption of Mount Pinatubo. In *Fire and mud, eruptions and lahars of Mount Pinatubo, Philippines* (eds CG Newhall, RS Punongbayan), pp. 545–570. Washington, DC: University of Washington Press.
122. Sewell DA. 2001 Earth, air, fire and water. An elemental analysis of the Minoan eruption of Santorini volcano in the Late Bronze Age. PhD thesis, University of Reading, UK.
123. Begèt JE, Gardner C, Davis K. 2008 Volcanic tsunamis and prehistorical cultural transitions in Cook Inlet, Alaska. *J. Volcanol. Geotherm. Res.* **176**, 377–386. (doi:10.1016/j.jvolgeores.2008.01.034)