Volcanic Eruption-Induced Tsunami in Indonesia: A Review

B W Mutaqin¹,², F Lavigne², D S Hadmoko¹, and M N Ngalawani¹

¹ Department of Environmental Geography, Faculty of Geography, Universitas Gadjah Mada, Sekip Utara, Bulaksumur, 55281 - Indonesia
² Université Paris 1 Panthéon Sorbonne, Laboratoire de Géographie Physique UMR 8591, Meudon, 92190 - France

Abstract. Tsunami, as a secondary hazard, can be triggered by tectonic earthquakes with its epicenter in the ocean floor, submarine volcanic eruptions, submarine landslides, meteor, or bomb at the ocean. Although volcanic eruption-induced tsunami events rarely happen, however, some events ever had a major impact, e.g., the 1741 CE eruption of Oshima-Oshima Volcano in Japan, the 1792 CE of dome collapse of the Mayuyama volcano in Japan, and the 1883 CE of Krakatoa tsunami in Indonesia. This review represents a brief database of the volcanic eruption-induced tsunami in Indonesia during the Holocene era. The largest historical tsunami due to volcanic activities happened in the 1883 CE in South Lampung. Pyroclastic flows from Krakatoa eruption reached the sea and triggered a tsunami with a run-up of 41.00 m, resulting in 36,000 death tolls. With this review, the purpose is to improve our knowledge of tsunami hazard and risk in Indonesia, especially those caused by volcanic activities, since Indonesia is known as a volcano-rich country, with more than 130 active volcanoes from a total of 400 volcanoes.

1. Introduction
The word tsunami comes from the Japanese terms, "Tsu" (port) and "nami" (wave). In general, the tsunami may be interpreted as an ocean wave or series of waves with a long period generated by inevitable disturbances that occur in the marine environment and can affect the coastal environment. These disturbances are can in the form of a tectonic earthquake with its epicenter in the ocean floor, submarine volcanic eruptions, submarine landslides, meteor, or bomb at the ocean. Therefore, the tsunami also is known as a secondary hazard, while the primary hazard is the geophysical phenomenon as mentioned above [1]. There are several causes of the volcanic eruption-induced tsunami, such as an underwater explosion, airwave generated by the blast, pyroclastic flows that entered to the sea, the collapse of an underwater caldera, subaerial failure, and submarine failure(Figure 1; [2]).

The global historical tsunami database from National Geophysical Data Center - NOAA shows that volcanic activity triggered at least 139 tsunamis in the world since 2100 BCE. The most prominent tsunami that triggered by volcanic activity in historical times in the world occurred in Thera Island, Greece (1610 BCE) and in W. Hokkaido Island, Japan on 29 August 1741 CE. Both tsunamis reached 90-meter maximum run-up. The most recent volcanic eruption-induced tsunami occurred in Kadovar Island, Papua New Guinea on 9 February 2018. The collapse of the lava dome at Kadovar’s SE Coastal Vent caused 5 - 6 minor tsunamis with less than 1-meter run-up [3].
Probably the most-frequently volcanic eruption-induced tsunamis occurred in Montserrat, Soufriere Hills Volcano. Since 1997, there are four documented tsunamis due to volcanic activity, i.e., on 26 December 1997, 20 January 1999, 12 July 2003, and 20 May 2006 [4, 5, 6, and 7]. In 1997, volcanic debris slide generated a wave with a maximal height up to 3-meter and flooded the Old Bay area.
which located 10 km from the source of the tsunami [4]. The height of the 1999-tsunami waves in Soufriere Hills reached two meters but weakened immediately [6]. The 2003 pyroclastic flow material reached the ocean and generated an 8.5-meter high tsunami on the eastern coast of Montserrat and up to 0.5-meter in Guadeloupe [7]. Furthermore, the 2003 tsunami had a 4-meter wave height which was identified by its debris at Spanish Point, about 100-150 meters from the shoreline [5]. In 2006, Montserrat Volcano Observatory explained that a 90-million m$^3$ of the lava dome has collapsed and generates a tsunami that reaches Guadeloupe with up to 1-meter of wave height based on tide-gauge measurement.

Tsunamis caused by volcanic activities have resulted in the death of more than 54,000 persons, which is equal to 25% of total victims due to volcanism [8]. Although volcanic eruption-induced tsunami events rarely happen, however, some events ever had a major impact, e.g., the 1792 CE of dome collapse of the Mayuyama volcano in Kyushu (15,030 death tolls), the 1741 CE eruption of Oshima-Oshima Volcano in the Japan Sea (1,607 death tolls), and the Krakatoa tsunami, Indonesia in 1883 CE (36,000 death tolls) [9].

Besides the tsunami following the 1883 CE eruption of Krakatoa volcano, in general, volcanic eruption-induced tsunamis in Indonesia are not well-studied yet, neither their causes nor their consequences. This review represents a brief database of the volcanic eruption-induced tsunami in Indonesia during the Holocene era. With this review, the purpose is to improve our knowledge of tsunami hazard and risk in Indonesia, especially those caused by volcanic activities, since Indonesia is known as a volcano-rich country, with more than 130 active volcanoes from a total of 400 volcanoes (Figure 2).

**Figure 2.** An example of a multiplatform application for geo-hazard mitigation and assessment for volcanic activities in Indonesia from Indonesian Centre for Volcanology and Geological Hazard Mitigation (CVGHM) http://magma.vsi.esdm.go.id/. The color differences of the volcano on the map are related to the current status of the volcano, e.g., normal (green); minor activity (yellow); warning (orange); and erupting (red).

### 2. Studies of the volcanic eruption-induced tsunami in Indonesia

Numerous works of literature are reviewed and summarized related to the volcanic eruption-induced tsunami in Indonesia since 2100 BCE. Table 1 and Figure 3 provide extensive selected works of literature that describe tsunami events triggered by volcanic activities in Indonesia during the Holocene era.
Table 1. Volcanic eruption-induced tsunami in Indonesia since 2100 BCE.

| No. | Years | Location | Max Run-up (m) | Cause of tsunami |
|-----|-------|----------|----------------|------------------|
| 1.  | 416   | Krakatau, South Lampung | Questionable   |
| 2.  | 1608  | Gamalama, Ternate Island  |               |
| 3.  | 1659  | Teon volcano, Banda Sea  | 1.5            | Pyroclastic flows? |
| 4.  | 1673  | Gamkonora, Halmahera      |Earthquake & landslides |
| 5.  | 1771  | Gamalama, Ternate Island  |               |
| 6.  | 1815  | Tambora, Sumbawa Island   | 3.5            | Pyroclastic flows |
| 7.  | 1837  | Peuetsagu, Banda Aceh     |Questionable    |
| 8.  | 1840  | Gamalama, Ternate Island  |               |
| 9.  | 1845  | Soputan, Celebes Sea      |Questionable    |
| 10. | 1856  | Awu volcano, Sangihe Is. |Pyroclastic flows |
| 11. | 1871  | Ruang, North Sulawesi     | 25             | The collapse of the lava dome |
| 12. | 1883  | Krakatau, South Lampung   | 41             | Pyroclastic flows |
| 13. | 1883  | South of Java, Java Island| 35            | Pyroclastic flows? |
| 14. | 1884  | Krakatau, South Lampung   |Underwater explosion? |
| 15. | 1889  | Banua Wuhu, Sangihe Island| 4             | Underwater explosion |
| 16. | 1892  | Awu volcano, Sangihe Is. | 0.75           | Pyroclastic surges |
| 17. | 1918  | Banua Wuhu, Sangihe Is.   | 0.08           | Underwater explosion |
| 18. | 1919  | Banua Wuhu, Sangihe Is.   | 5              | Underwater explosion |
| 19. | 1928  | Paluweh Island, Flores Sea| 10            | Volcanic landslide? |
| 20. | 1928  | Krakatau, South Lampung   |Underwater explosion |
| 21. | 1930  | Krakatau, South Lampung   |Underwater explosion |
| 22. | 1963  | Agung volcano, Bali       |               |
| 23. | 1979  | Iliwerung, Lembata        | 9              | Volcanic landslide |
| 24. | 1981  | Krakatau, South Lampung   | 2              | Volcanic landslide? |

Figure 3. Volcanoes in Indonesia which their activities had triggered tsunami during the Holocene era.

3. Summary
The most significant historical tsunami due to volcanic activities in Indonesia happened in the 1883 CE in South Lampung. Pyroclastic flows from Krakatoa eruption reached the sea and triggered a tsunami with a run-up of 41.00 m, resulting in 36,000 death tolls. As the most deadly volcanic
eruption-induced tsunami in Indonesia, the Krakatoa tsunami in 1883 CE was well studied by several researchers [26, 27, 28, 29, 30, and 31]. This phenomenon is also well described either by eye-witness descriptions, i.e., by the Dutch shippers in 1883 CE [19]; as well as by geologic investigations. During two days, several rapid mass transfers from pyroclastics flow entered the sea and produce a tsunami with 42-meter of the maximal run-up in Merak, Banten, Indonesia [32, 33]. This tsunami reached Colon, Panama about 19,331 km away from the source with maximal run-up up to 0.4-meter [32].

CVGHM reported that the most recent Krakatoa activities happened on 22 September 2018. Small amounts of incandescent material fell into the sea, and lava flows on the south-southeast flank also reached the sea [34]. It means that the Krakatau volcano still categorized as a tsunami hazard, especially for the coastal area along the Sunda Strait. Therefore, it is necessary to improve the knowledge and preparedness of communities about the volcanic eruption-induced tsunami to avoid misperceptions related to tsunamis, as happened in April 2018, involving tsunami researcher from Agency for the Assessment and Application of Technology (BPPT), journalists, communities, local government, and the police [35]. Furthermore, increased activity of Agung volcano on 25 July 2018, Soputan volcano on 3 October 2018, and the most recent, Gamalama volcano on 4 October 2018, should make the government and the local people increase their alertness and preparedness, take into account the fact that these volcanoes had triggered a tsunami in the past (see Table 1 and Figure 3).

Finally, this review provides information related to the volcanic eruption-induced tsunami, in this case, in Indonesia during the Holocene era. This information is crucial since Indonesia is known as a volcano-rich country with more than 130 active volcanoes, and probably several submarine volcanoes that remains unknown. However, volcanic eruption-induced tsunamis, comprehensively, are almost never put in the hazard information, neither volcanic hazard nor coastal hazard. Lack of information related to the volcanic eruption-induced tsunami will boost the risk in the next coastal volcanoes eruption; moreover, almost all major cities in Indonesia are located in the coastal area.

Acknowledgments
The first author would like to acknowledge the LPDP (Indonesia Endowment Fund for Education) scholarship fund (S-320/LPDP.3/2014), awarded by the Republic of Indonesia’s Ministry of Finance, for its financial support. This paper has been written as part of a collaborative project between Universitas Gadjah Mada and University Paris 1 Panthéon Sorbonne. We also wish to thank S. Badriah, Pendhoza, NDX Aka Familia, P. van Haver, and M.B. Mathers III for their support and encouragement during the writing process. Finally, the authors also would like to thank anonymous reviewers for their helpful comments on this paper.

References
[1] Smart G M Crowley K H M and Lane E. M 2016 Estimating tsunami run-up. Nat Hazards. 80(3) : 1933-1947. https://doi.org/10.1007/s11069-015-2052-8.
[2] Paris R Switzer A D Beloussova M Belousov A Ontowirjo B Whelley, P. L., Ulvrova, M. (2013). Volcanic tsunami: a review of source mechanisms, past events, and hazards in Southeast Asia (Indonesia, Philippines, Papua New Guinea). Nat Hazards. 70, 1 : 447-470. https://doi.org/10.1007/s11069-013-0822-8.
[3] National Geophysical Data Center / World Data Service (NGDC/WDS) 2018 Global Historical Tsunami Database. National Geophysical Data Center, NOAA. https://doi.org/10.7289/V5PN93H7. [3 April 2018].
[4] Lander J F Whiteside L S and Lockridge P A 2003 Two Decades of Global Tsunamis, 1982-2002. Science of Tsunami Hazards. 21(1) 3-88.
[5] Pelinovsky E Zahibo N Dunkley P Edmonds M Herd R Talipova T Kozelkov A and Nikokina I 2004 Tsunami Generated by the Volcano Eruption on July 12-13, 2003 at Montserrat, Lesser Antilles. Science of Tsunami Hazards. 22, 1 44-57.
[6] Pararas-Carayannis G 2006 Risk assessment of tsunami generation from active volcanic sources in the eastern Caribbean region. Caribbean Tsunami Hazard, Proc. of the NSF Caribbean
Tsunami Workshop, March 30-31, 2004, Aurelio Mercado-Irizary and Philip Liu, eds., World Scientific Publishing Co., Singapore, p91-137. https://doi.org/10.1142/9789812774613_0005.

[7] Mattioli G S Voight B Linde A T Sacks I S Watts P Widiwijayanti C Young S R Hidayat D Elsworth D Malin P E Shalev E Van Boskirk E Johnston W Sparks R S J Neuberg J Bass V., Dunkley P Herd R Syers T Williams P and Williams D 2007 Unique and remarkable dilatometer measurements of pyroclastic flow-generated tsunami. *Geology.* 35 (1), 25–28. https://doi.org/10.1130/G22931A.1.

[8] Latter J H 1981 Tsunamis of volcanic origin: Summary of causes, with particular reference to Krakatoa, 1883 *Bulletin Volcanologique.* 44, 3 : 467-490. https://doi.org/10.1007/10.1007/BF02600578.

[9] Paris R 2012. Signature morpho-sédimentaire des tsunamis et implications en terme de risques. *Mémoire de l'habilitation à diriger des recherches.* (Université Blaise Pascal, Clermont-Ferrand).

[10] Latief H Puspito N T and Imamura F 2000 Tsunami Catalog and Zones in Indonesia. *Journal of Natural Disaster Sci.* 22, 1 : 25–43 https://doi.org/10.2328/inds.22.25.

[11] Lockridge P A 1988 Historical Tsunami in the Pacific Basin. In: El-Sabh, M. I. and Murty, T. S. *Natural and Man-Made Hazards: Proceedings of the International Symposium held at Rimouski, Quebec, Canada, 3–9 August 1986*. Springer Science & Business Media. 868p. https://doi.org/10.1007/978-94-009-1433-9.

[12] Rastogi B K 2007 A historical account of the earthquakes and tsunamis in the Indian Ocean. In: Murty, T. S., Aswathanarayana, U., Nirupama, N. *The Indian Ocean Tsunami - Balkema-proc. and monographs in engineering, water and earth sci.* CRC Press. 528p.

[13] Soloviev S L and Go Ch N 1974 *A catalogue of tsunamis on the western shore of the Pacific Ocean 173-1968.* (Academy of Sciences of the USSR, Nauka Publishing House, Moscow) 439p.

[14] Berninghausen Wm H 1969 Tsunamis and seismic seiches of Southeast Asia. *Bulletin of the Seismological Society of America.* 59(1): 289–297.

[15] Heck N H 1947 List of seismic sea waves. *Bulletin of the Seismological Society of America.* 37(4): 269-286.

[16] Stothers R B 1984 The Great Tambora Eruption in 1815 and Its Aftermath. *Sci.* 224, 4654, 1191-1198. https://doi.org/10.1126/science.224.4654.1191.

[17] Verbeek R M 1886 *Krakatau.* (Batavia, Imprimerie de l’Etat) 567p.

[18] Rampino M R and Self S 1982 Historic eruptions of Tambora (1815), Krakatau (1883), and Agung (1963), their stratospheric aerosols, and climatic impact. *Quaternary Research.* 18(2), 127-143. https://doi.org/10.1016/0033-5894(82)90065-5.

[19] Simkin T and Fiske R 1983 *Krakatau 1883: The Volcanic Eruption and Its Effects.* (Washington, D.C.: Smithsonian Institution Press) 464p.

[20] Winchester S 2003 *Krakatoa, The Day the World Exploded: August 27, 1883,* (Harper Collins Publishers, New York, NY) 416p.

[21] Carey S Sigurdsson H Mandeville C and Bronto S 1996 Pyroclastic flows and surges over water: an example from the 1883 Krakatoa eruption. *Bulletin of Volcanology.* 57, 7 : 493-511. https://doi.org/10.1007/BF00304435.

[22] Stehn C E 1929 *The geology and volcanism of the Krakatau group*. Part 1. (4th Pacific science congress, Batavia, Guidebook) pp 1–55.

[23] Soloviev S L Go Ch N Kim K S 1992 *Catalog of tsunamis in the Pacific, 1969-1982.* (Academy of Sciences of the USSR, Moscow) 208p.

[24] Lassa J 2009 The forgotten disasters? Remembering The Larantuka and Lembata disasters 1979-2009. *Journal of NTT Studies,* 1(2): 159-18.

[25] Carmus G Bourgaud A Vincent P M 1987 Petrologic evolution of Krakatau (Indonesia): Implications for a future activity. *Journal of Volcanology and Geothermal Research.* 33(4):.
299-316. https://doi.org/10.1016/0377-0273(87)90020-5.
[26] Francis P W 1985 The origin of the 1883 Krakatau tsunamis. Journal of Volcanology and Geothermal Research. 25, 3-4, 349-363. https://doi.org/10.1016/0377-0273(85)90021-6.
[27] Yokoyama I 1987 A scenario of the 1883 Krakatau tsunami. Journal of Volcanology and Geothermal Research. 34, 1-2, 123-132. https://doi.org/10.1016/0377-0273(87)90097-7.
[28] Van den Bergh G D Boer W de Haas H van Weering Tj C E van Wijhe R 2003 Shallow marine tsunami deposits in Teluk Banten (NW Java, Indonesia), generated by the 1883 Krakatau eruption. Marine Geology. 197, 1-4, 13-34. https://doi.org/10.1016/S0025-3227(03)00088-4.
[29] Giachetti T Paris R Kelfoun K Ontowirjo 201 Tsunami hazard related to a flank collapse of Anak Krakatau Volcano, Sunda Strait, Indonesia. Geological Society London, Special Publications 361 79-90. https://doi.org/10.1144/SP361.7.
[30] 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. Bulletin of Volcanology. 76 814. https://doi.org/10.1007/s00445-014-0814-x.
[31] Paris R Ramalho R S Madeira J Ávila S May S M Rixhon G Engel M Brückner H Herzog M Schukraft G Perez-Torrado F J Rodriguez-Gonzalez A Carraced J C Giachetti T 2018 Mega-tsunami conglomerates and flank collapses of ocean island volcanoes. Marine Geology. 395, 168-187. https://doi.org/10.1016/j.margeo.2017.10.004.
[32] Choi B H Pelinovsky E Kim K O and Lee J S 2003 Simulation of the trans-oceanic tsunami propagation due to the 1883 Krakatoa volcanic eruption. In Tsunamis, Tinti, S., and Pelinovsky, E. Nat. Hazards Earth Syst. Sci. 3, 5, 321-332. https://doi.org/10.5194/nhess-3-321-2003.
[33] Freundt A 2003 Entrance of Hot Pyroclastic Flows into the Sea: Experimental Observations. Bulletin of Volcanology. 65, 2-3, 144-164. https://doi.org/10.1007/s00445-002-0250-1.
[34] CVGHM 2018 Pers Rilis Aktivitas Gunungapi Anak Krakatau, Rabu 3 Oktober 2018. http://vsi.esdm.go.id/index.php/gunungapi/aktivitas-gunungapi/2445-pers-rilis-aktivitas-gunungapi-anak-krakatau-rabu-3-oktober-2018. [12 October 2018].
[35] The Jakarta Post 2018 Banten Police drop plan to summon scientist. Jakarta | Wed, April 11, 2018. http://www.thejakartapost.com/news/2018/04/11/banten-police-drop-plan-to-summon-scientist.html. [12 October 2018].