Identification and ranking of subaerial volcanic tsunami hazard sources in Southeast Asia

Supplementary Material C - Tsunami source volcanoes

Looking at individual volcanoes, our catalogue and ranking have identified a large number of potentially hazardous ones regarding the production of tsunamis. In the high hazard category are the Indonesian volcanoes Anak Krakatau, Batu Tara, Gamalama, Iliwerung, Sangeang Api, Karangetang, Sirung, Wetar, Nila, Ruang and Serua. In Papua New Guinea high risk volcanoes include Kadovar, Ritter Island, Rabaul, Manam, Langila, Ulawun and Bam. In the Philippines there is only one high risk volcano - Didicas. Below, we briefly elaborate on the aspects that contribute to the high score of these volcanoes, speculate on the nature of future tsunamis that can be expected from them, and assess which particular volcanoes should be prioritised for tsunami monitoring and forecasting. Anak Krakatau, Kadovar, Nila and Batu Tara are featured in the main paper.

Iliwerung (Fig. S4 a-b): The small cone is situated at the southern coast of Lembata Island, where it forms a complex of vents and lava domes, including some submarine ones. The main subaerial cone is located above a steep flank, providing a direct path towards the sea. The volcano is also known for frequent eruptions with the last one being submarine in 2021 (Global Volcanism Program, 2013), and has three recorded historical tsunamis in 1973, 1979, and 1983 (Table 1), as well as signs of a past sector collapse in its morphology. Considering all above, Iliwerung is one of the highest ranking volcanoes in our catalogue. All known mechanisms of volcanogenic tsunami generation may be relevant here, especially large submarine or coastal explosions, pyroclastic flows and flank or lava dome collapses. A potential tsunami would likely affect all Lesser Sunda Islands and well as Timor in a short amount of time.

Gamalama (Fig. S4 c-d): The volcano forms a large, nearly circular island in the north of Indonesia as part of the Maluku Islands at the Molucca Sea. It has the city Ternate on its eastern flank, which has approximately 205,000 inhabitants, making it the largest and most densely populated city in the province and an important economic centre. Since the volcano is very frequently active with its last eruption in 2018, it has both a history of deadly eruptions such as in 1775 and 2011 (Hidayat et al., 2020) as well as tsunamis in 1608, 1771, 1772 and 1840 (Table 1). Since most of the volcano's flanks are not exceptionally steep, the most likely causes for tsunamis are far-reaching pyroclastic flows or eruptions on the lower flanks, however, partial collapses from the steeper summit region should also be considered. While Ternate is the largest populated area affected, it should be noted that a potential tsunami could also affect the other nearby islands as well as the western coast of Halmahera, the eastern coast of North-Sulawesi as well as the Islands Taliabu and Mangole.

Sirung (Fig. S4 e-f): Similar to Iliwerung, Sirung forms a peninsula towards the south of the Lesser Sunda Islands. It is located on Pantar Island and forms a multifaceted complex including a large caldera, a steep stratocone and lava domes. Recent eruptions have been dominantly phreatic, although the morphology suggests that multiple eruptive

styles are possible, including potential large caldera-forming eruptions. While these are less likely to occur, the resultant pyroclastic flows would need to travel less than 3 km downhill to reach the sea. As with Iliwerung, a potential tsunami would rapidly affect all Lesser Sunda Islands and the north coast of Timor.

Ritter Island (Fig. S4 i-j): After its catastrophic sector collapse and tsunami in 1888 much of the island's subaerial edifice remains destroyed, leaving only an elongated ridge as a remnant scar. While this may exaggerate the morphological metrics applied to our ranking (the island largely consists of a west-facing scar), the volcano has still produced multiple tsunamis after the large collapse, which occurred in 1972, 1974 and 2007. This demonstrates the volcano's continued potential to produce tsunamis, both by explosions and sector failures of the subaerial or submarine edifice, but also a scenario similar to the recent Hunga Tonga-Hunga Haʻapai eruption (Somerville et al., 2022) should be considered since both these volcanoes have their main vents located in shallow waters.

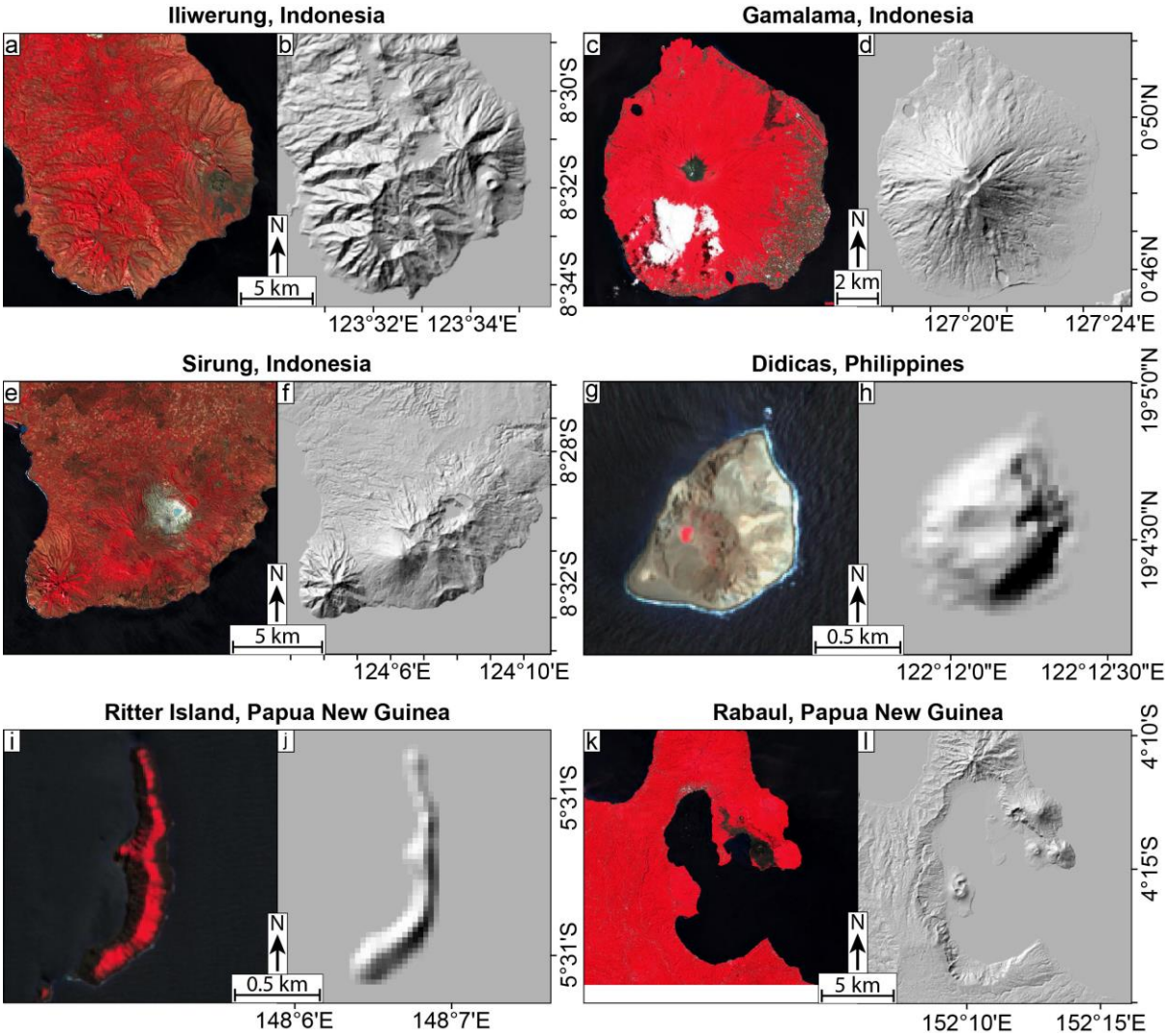

Figure S4: Sentinel-2 images using bands 8 (NIR), 4 (red), and 3 (green) and DEM for the individual volcanoes Iliwerung (a, b), Gamalama (c, d), Sirung (e, f), Didicas, (g, h), Ritter Island (i, j) and Rabaul (k, l). Note that volcanoes are shown on different scales.

Rabaul (Fig. S4 k-l): The large 8 by 14 km Rabaul caldera forms a bay south of the Gazelle Peninsula in the northeast of New Britain. Here, it is questionable how well our morphological criteria for the ranking represent the tsunami hazard as the subaerial edifice is limited to the Tavurvur and Vulcan cones, which are on opposite ends of the submerged caldera. We chose Tavurvur since it was the site of Rabauls most recent eruption in 2014. On the other hand, the volcano's tsunamigenic potential has been demonstrated in 1878, 1937 and 1994, where all tsunamis occurred in conjunction with significant explosive eruptions. Since the caldera is mostly submerged, tsunamis may be generated not only by pyroclastic flows and edifice collapses at the two main cones, but also underwater or coastal explosions. Even otherwise less significant phreatic eruptions around the hot springs adjacent to Tavurvur may be considered here. A tsunami would affect the city of Rabaul directly inside the bay, but may also spread to the northern coast of New Britain, the western coast of New Ireland and the Duke of York Island.

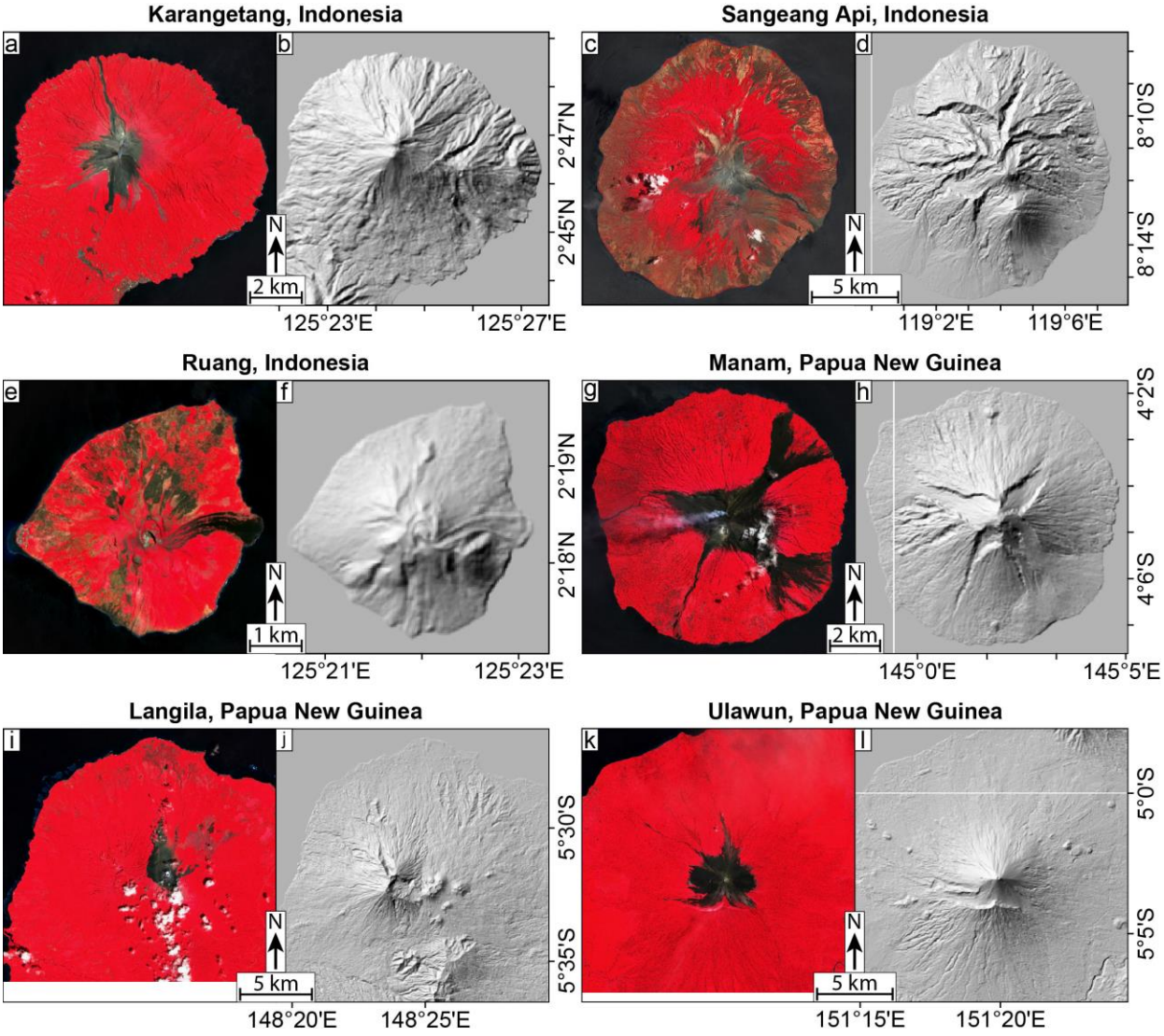

Figure S5: Sentinel-2 images using bands 8 (NIR), 4 (red), and 3 (green) and DEM for the individual volcanoes Karangetang (a, b), Sangeang Api (c, d), Ruang (e, f), Manam, (g, h), Langila (i, j) and Ulawun (k, l). Note that volcanoes are shown on different scales.

Didicas (Fig. S4 g-h): Lava dome extrusion from volcano formed a small island in 1952 in the Luzon Strait in the north of the Philippines. Multiple repeated eruptions are known from this volcano since 1773, which were mostly submarine, although some islands were formed and destroyed prior to the current island. The last eruptive episode ended in 1978, but had produced a tsunami in 1969. Due to the small size of the young island, future activity has the potential to cause tsunamis by full or partial failure of the edifice, underwater explosions and lava dome collapses, should further domes grow. A tsunami from this location is likely to affect the Babuyan and Batanes Islands as well as the northern coast of Luzon. We note that Didicas was not used for the tsunami travel time simulations.

Karangetang, Sangeang Api and Manam (Fig. S5 a-d, g-h): These three volcanoes all form larger, near circular volcanic islands (diameters between 8-15 km), with Karangetang connecting to the southern part of Siau Island. They are among the most active volcanoes on this list, having regular and dominantly explosive eruptions of varying intensity. Currently, Karangetang and Manam have ongoing eruptions at the time of writing and Sangeang Api had its last in 2020. While the lower flanks are mostly forested with gentle slopes, the summit regions are very steep and barren due to the constant activity. Manam and Sangeang Api are also heavily dissected, suggesting multiple partial edifice failures have occurred in their geological history. Despite this, no historical tsunamis are known from any of these volcanoes, but gravitational mass movements like pyroclastic flows from large explosions or lava dome collapses as well as landslides from edifice failures have direct downhill paths into the sea in multiple directions, but would need to travel between 3 and 7 km. This makes a scenario in which a tsunami is generated only likely for larger eruptions. But as Anak Krakatau demonstrated, significant sector failures may also occur without significant eruptions (Williams et al., 2019).

Ruang, Serua, Nila, Wetar and Bam (Fig. 2, S5 e-f, S6 a-f): The volcanoes grouped here are the smaller volcanic Islands (diameters under 5 km). Naturally, these are primed for tsunami generation as their flanks are small and steep, with eruptions occurring close to the sea, however, most of these volcanoes are not as frequently active compared to the larger islands Karangetang, Sangeang Api and Manam. Their last eruption ranges from decades (Ruang, Nila, Wetar, Bam) to a century ago (Serua) and - with the exception of Ruang in 1871 and 1889 - none of them have associated historical tsunamis. On the other hand, all islands show signs of past edifice collapses, which is confirmed for Bam through submarine debris avalanche deposits (Silver et al., 2009), which underlines their tsunamigenic potential. Ongoing hydrothermal alteration is also visible on the flanks of Wetar, Nila and Serua, potentially weakening their flanks. For the consideration of future tsunami hazards posed by these volcanoes, especially since these smaller islands with little to no habitation are less studied, *it is important to have adequate monitoring in place as renewed eruptive activity would make these volcanoes particularly likely tsunami sources*. Partial flank failures similar to Anak Krakatau in 2018, both subaerial and submarine are likely causes, but explosions and pyroclastic flows are also possible.

Langila and Ulawun (Fig. S5 i-l): The two Papua New Guinean volcanoes Langila and Ulawun are large and steep stratovolcanoes, very similar to large volcanic Islands such as Karangetang, both in terms of morphology and activity (frequent explosive eruptions in recent years) as well as no known historical tsunamis. One major difference is that

both are located on land and have only parts of their flanks facing the sea, west to northeast for Langila and only northwest for Ulawun. This also makes coastal flank eruptions less likely and the main tsunami hazard stems from far-reaching pyroclastic flows (up to 9.5 km for Ulawun) or major edifice failures (both volcanoes have signs of past collapses).

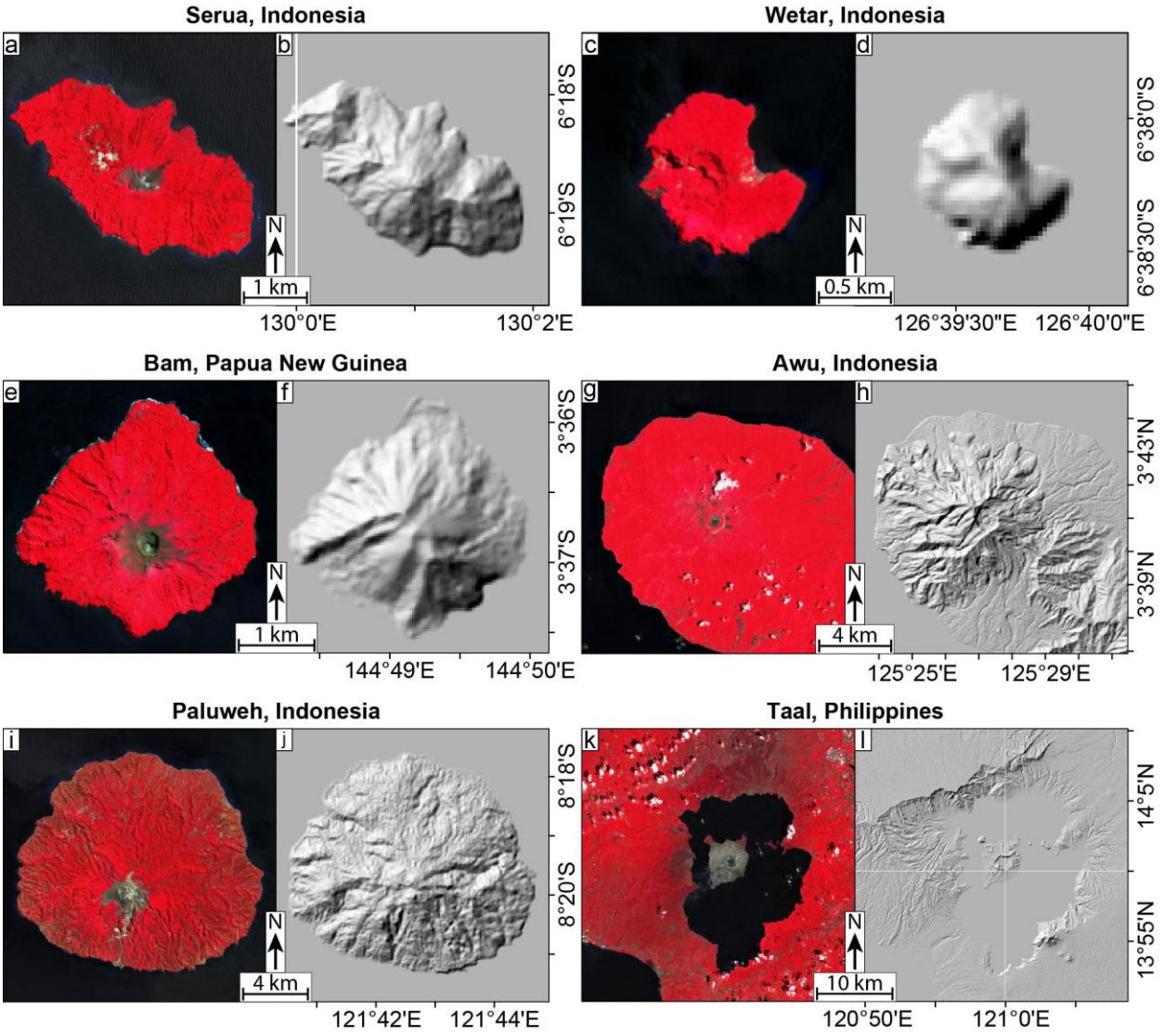

Figure S6: Sentinel-2 images using bands 8 (NIR), 4 (red), and 3 (green) and DEM for the individual volcanoes Serua (a, b), Wetar (c, d), Bam (e, f), Awu, (g, h), Paluweh (i, j) and Taal (k, l). Note that volcanoes are shown on different scales.

Other relevant volcanoes (Fig. S6 g-l): This final paragraph briefly highlights some volcanoes that were not classified into the high hazard category, but should nonetheless be considered for tsunami assessments. The Indonesian

volcanoes Awu and Paluweh (or Rokatenda) and the Philippine volcano Taal do not have as tall and steep edifices as some other volcanoes on this list and thus received a lower score. However, all have a history of producing tsunamis with hundreds to thousands of fatalities as a result of their eruptions (Table 1). Provided that eruptions resume it is likely that such a scenario can happen again in the future. The latest eruption at Paluweh occurred between October 2012 and August 2013 in which an effusive-explosive eruption produced PDCs that caused 5 fatalities, however, fortunately the pyroclastic materials did not trigger tsunami (Primulyana et al., 2017). An eruption at Taal is currently ongoing at the time of writing, highlighting the relevance of these volcanoes. Similarly, there are a number of small volcanic islands that did not score as high because they are not as active, meaning their last eruption occurred decades to centuries ago. For Indonesia, these are Teon, Manuk, Wurlali, and Banda Api. Here, the situation is comparable to Kadovar before it erupted in 2018, the islands could become a significant tsunami hazard if new eruptive activity resumes.

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