A brief history of tsunamis in the Vanuatu Arc

Jean Roger[1*], Bernard Pelletier[2]

[1]Earth and Structure Processes Department, GNS Science, Lower Hutt, New Zealand
[2]Institut de Recherche pour le Développement, UMR Géoazur, Nouméa, Nouvelle-Calédonie, France

Correspondence to: Jean H.M. Roger (j.roger@gns.cri.nz)

Abstract. The archipelagos of Vanuatu and Eastern Solomon Islands, scattered over 1500 km along the Vanuatu Arc, include dozens of inhabited volcanic islands exposed to many natural hazards which impact their populations more or less severely. Due to the location of these islands upon a subduction interface, known as the Vanuatu Subduction Zone, tsunamis triggered by earthquakes, volcanic eruptions, and landslides locally, regionally and in the far field, represent a permanent threat. If catalogues already listed tsunamis having occurred in the Vanuatu Arc, they were not exclusively focusing on this region. This study goes further in the listing of tsunamis reported and/or recorded in the Vanuatu Arc, analysing existing catalogues, historical documents, and sea-level data from the 5 coastal tide gauges located in Vanuatu at Port Vila (Efate), Luganville (Santo), Litzlitz (Malekula) and Lenakel (Tanna) and in the Eastern Solomon Islands Province at Lata (Ndende). It allows to identify 100 tsunamis since 1863, 15 of them showing wave amplitude and/or run-up height of more than one meter and 8 between 0.3 and 1 m. If it is known that some tsunamis occurred by the past, information about the wave amplitude or potential run-up is sometime lost (15 events). Also, tsunamis reported in neighbouring islands like New Caledonia, but not reported or recorded in the Vanuatu Arc are discussed, as well as debated events or events with no known origin(s).

1 Introduction

1.1 Tectonic context

Located in the southwest Pacific region, the Vanuatu Subduction Zone (called VSZ hereafter) and its associated Vanuatu Arc (previously known as New Hebrides Arc) belong to the Pacific Ring of Fire and result from the convergence between the Australian and the Pacific plates. The Vanuatu Arc extends over 1500 km and includes the islands of Vanuatu (65 inhabited islands, over a total of ~83), but also in its southern part the uninhabited Matthew and Hunter Islands (New Caledonia), and in its northern part most of the islands of the easternmost province of Solomon Islands (known also as Temotu Province and formerly known as Santa Cruz Islands Province; Figure 1). Due to the morphology of the VSZ and to several microplate boundaries at the rear of the VSZ in the North Fiji Basin (NFB on Figure 1), the arc can be divided into four segments and the rate of convergence at the trench varies along the arc from 35 mm/year in the central segment, 48 mm/year in the southeasternmost segment (around Matthew and Hunter Islands), 90 to 120 mm/year in the southern segment, to a maximum of 160 mm/year for the northern segment (Pelletier et al., 1998; Calmant et al., 2003; Figure 1).

In the central part of the Vanuatu Arc, the islands are located along three lines or ranges parallel to the subduction trench (Carney and MacFarlane, 1982). The closest line to the trench, i.e. the Western Range, is the oldest volcanic line and contains Early to Middle Miocene volcanic series outcropping in Malekula in the south, Santo and Torres Islands in the far north. The middle line, i.e. the Central Range, is the most recent and extends all along the arc; it is composed of Plio-Quaternary volcanic rocks and active volcanoes from Matthew and Hunter islands (New Caledonia) in the south to Tinakula Island (Solomon Islands) in the north through Aneityum, Tanna, Erromango, part of Efate, Shepherd Islands, part of Epi, Lopevi, Paama, Ambrym, Ambae, Gaua, Banks Islands, then Vanikoro, Utupua and Santa Cruz Islands (Solomon Islands). The furthest line to the trench, i.e. the Eastern Range, is composed of Mio-Pliocene volcanic series outcropping in Pentecost and Maewo in the north. These three lines of islands are the result of complex processes associated with the convergence history between the Australian and Pacific plates, including subduction polarity reversal. The islands of the Western and Eastern Ranges and part of the islands of the Central Range exhibit coral reef terraces due to the uplift of the overriding plate (Taylor, 1992).

1.2 Human occupation & remnants of history

In 2003, the Teouma Lapita site is discovered in Efate Island, Central Vanuatu (Bedford et al., 2004). Further investigations revealed that this is the oldest Lapita site of the whole Western Pacific Ocean, with dating methods providing settlers occupation c. 3,000 cal. BP (Bedford et al., 2006, 2007; Petchey et al., 2014). This estimated date has been more recently confirmed through DNA analyses of bones from the Teouma burial site: Vanuatu has been occupied by humans having travelled from Asia only since c. 3,000 years (Skoglund et al., 2016). The first Europeans, led by the Portuguese explorer Pedro Fernandez De Quiros, discovered the archipelago in 1606 (named Iles St Esprit), but effective sparse settlement occurred only from 1768 when the French explorer Louis Antoine de Bougainville re-discovered these islands, soon followed by James Cook (in 1774) who mapped the archipelago and named it New Hebrides, referring to some Scottish islands (Aldrich, 1993; Woodward, 2014). Some settlers from both France and England lived in those islands since then, without one of the two countries claiming sovereignty. It is only in 1906 that they decided to establish a condominium, which lasted until the independence of the Republic of Vanuatu in July 1980. The lack of written history on the native people side and the very recent occupation from Europeans lead to the fact that potential written history of Vanuatu began only ~150 years ago mainly by missionaries, and with it, the potential information related to tsunamis.

In the Solomon Islands, human occupation is believed to occur much earlier in history, ca 30,000-40,000 years ago during the Pleistocene (Friedlaender et al., 2002; Walter and Sheppard, 2009). However, the southeasternmost group of islands of the Solomon Archipelago, the so-called Santa Cruz Islands, were probably colonized by the first Lapita settlers only ca. 3,000 years ago according to populations DNA analysis (Friedlaender et al., 2002) and archaeology, including radiocarbon dating (Green, 1991; Kirch and Swift, 2017). The diversity of cultures and indigenous languages (63 different languages reported by Tryon and Hackman, 1983) in the archipelago makes the task complex when establishing a chronology of occupation. The only certainty is that the first Europeans having reached the Santa Cruz Islands were led by the Spanish explorer Álvaro de Mendaña de Neira in 1568. Navigators, especially whalers, really travelled within this region only from the late 1700s, early 1800s, and the first missionaries had contact with coastal people from 1845, settling in 1898 with the foundation of a Roman Catholic mission (Hilliard, 1974). The Melanesian Mission settled in the Eastern Outer Islands in 1849 (Tryon and Hackman, 1983). In this region, the settlement of Europeans is generally associated to written reports of natural phenomena, including earthquakes, volcanic eruptions, and tsunamis, which are not found before their arrival. For information, Tryon and Hackman (1983) indicate that the Solomon government did not provide public education until 1945, which was therefore until then limited to the churches' education.

However, as in other islands in the Pacific Region, kastom stories related to natural disaster exist in the traditional oral knowledge in Vanuatu and probably in the Eastern Solomon Islands. Geological evidence and oral history of tsunamis in Vanuatu have been firstly reported by Goff et al. (2008) who related a collection of kastom stories about tsunamis and volcanic eruptions from villages in Efate, Epi and Tongoa.

1.3 Tsunami catalogues and previous works on tsunami in Vanuatu Arc

Event catalogues, whether they collect information about tsunamis, volcanic eruptions, landslides, etc., are a crucial step in studying natural hazards. In fact, hazard assessment needs reliable historical data to validate the models used for building evacuation maps, land use planning, etc. Several methodologies exist for building tsunami catalogues, three of them being the most common. The first one, and probably the most applied throughout the World, consists in investigating historical documents (including reports, journal articles, drawings, paintings, etc.) preserved in archives, as well as collecting testimonies from people (directly from themselves, or reporting what someone else told the interviewed person, about oral tradition for instance, which is very common in the Pacific Islands). The second one depends on the availability of maregraphic or sea-level data: the installation of tide gauges, or lately, tsunami coastal gauges and DART stations, provides to scientists and risk managers direct and reliable observations/records of tsunamis waves, associated with critical values like wave amplitude, periodicity, polarity, frequency content, etc. The third methodology relies onto the sedimentological archives of tsunamis: when impacting the coast, tsunami waves are sometimes able to bring marine material onshore, which eventually deposited afterwards. If the environment allows their conservation, typically in swamps or depressed areas showing high rate of sedimentation, then these sediments can be preserved during millennia. Their analysis requires caution because, for example, small tsunami related deposits can easily be confused with other marine submersion deposits like those brought by storm or strong long-period swells (e.g., Shanmugam, 2012; Costa et al., 2018), or bioturbation can literally destroy the sedimentary structures (e.g., Spiske et al., 2020).

In Vanuatu and Eastern Solomon Islands, the limited written history (~150 years), associated to the very recent and limited number of only 5 coastal gauges - 4 in Vanuatu, located firstly in Port Vila (Efate) since 1977, then Luganville (Santo) in 1993 and more recently in Lenakel (Tanna) and Litzlitz (Malekula) in 1996, and 1 in Lata (Ndende, Eastern Solomon Islands Province) since 2010 (see details in Table 1) - leads to a very short and incomplete history of tsunamis, which largest ones could have return periods of hundreds to thousands of years. In addition, tsunamis triggered by landslides or volcanic eruption are known to have sometimes a very limited impact zone and would not be recorded on gauges located tens to hundreds of kilometres away from their source.

Although the Vanuatu and Eastern Solomon Islands are located on a major subduction zone and thus are potentially subjected to tsunamis triggered by earthquakes, volcanic eruptions and submarine landslides, there is almost no work on paleotsunamis based on tsunami deposits, except the one from Goff et al. (2008) on Efate, Epi and Tongoa, mainly focused to address the possible tsunami of the Kuwae eruption in the mid-15 century, and the present-day study by a CNRS-IRD-Univ. Clermont-Ferrand team organized in June 2023 on Efate, Tanna and Aneityum and mainly focused on the predecessors of the 1875 and 1878 major events.

Previous works on historical tsunami catalogues in the Vanuatu Arc region are those of Soloviev and Go (1974) on the western shore of the Pacific Ocean for the 1863-1967 period and Louat and Baldassari (1989) on the New Caledonia-Vanuatu region for the 1927-1989 period.

Specific studies focused on some recent major earthquakes and associated tsunamis, as for example, the November 1999 East Ambrym event in the central VSZ (Pelletier et al. 2000, Ioualalen et al. 2006), the January 2002 Efate event (Tendrayen, 2006), the February 2013 Santa Cruz event in the northern VSZ (Fritz et al., 2013), and the December 2018 (Roger et al., 2021), February 2021 (Roger et al., 2023a) Loyalty Islands events located in the southern VSZ.

The tide gauge records used in the present study cover the period from 15 January 1993 (only in Port Vila) to 30 June 2023. The sampling rate from 1993 to 2012 is 6 minutes and goes to 1 minute from late May 2012. The metadata is accessible on the Bureau of Meteorology (BOM) website: http://www.bom.gov.au/ntc/IDO50000/IDO50000_57320.pdf. Another record was available for Port Vila for the period from 1977 to 1982 (https://uhslc.soest.hawaii.edu/data/?rq). Unfortunately, the data was digitized from paper records, and that was done with hourly spot samples, which shows too poor resolution to help identifying any tsunami waveforms, a priori without conservation of the original records (P. Thomson, University of Hawaiʻi Sea Level Center, Pers. Comm., 2023).

The other coastal gauges have been installed in June 2010 on Lata Wharf, Ndende, 15 May 2013 in Luganville and 27 May 2016 in Lenakel and Litzlitz. These four stations have a sampling rate of 1 minute. The Lata Wharf gauge worked between 11 June 2010 and 27 October 2019 when it failed (M. Davis, Bureau of Meteorology, Australia, Pers, Comm., 2023). For this study we accessed data from 24 May 2011 to 27 October 2019 provided by BOM upon our request. This data shows some gaps; however, it was possible to use it for this study.

For information, in October 2022 a tsunami watch camera has been associated to the coastal gauge located at Litzlitz (https://www.jica.go.jp/Resource/vanuatu/english/office/topics/221023.html).

2. Data collection & methodology

The actual list of tsunamis having been recorded in the Vanuatu Arc and reported in global tsunami databases like the NOAA/NGDC tsunami database (NGDC/WDS, 2023) or the TL/ICMMG Global Historical Tsunami Database (TL/ICMMG, 2023) is not clear as these databases do not really help to distinguish tsunami triggered in a region and/or tsunami recorded in that region. As an example, the request on the NOAA/NGDC tsunami database for Country Vanuatu resulted of 36 events with origin in Vanuatu from 1863 to 2016. A more accurate search using the geographic extent 161°E/175°E/9°S/25°S provided 83 events between 1863 and 2023, none of them showing an origin out of the region. The same requests in the TL/ICMMG Global Historical Tsunami Database provided 30 and 86 events, respectively, with origin in Vanuatu between 1875 and 2023. In both cases, the tsunamis triggered at the Vanuatu subduction zone after 2016 have been located in New Caledonia/Loyalty Islands probably because that was the closest land to the source location, and tsunamis generated out of the region, but recorded in the region, are not listed.

If these tsunamis have generally been triggered by earthquakes, some of them may have followed volcanic eruptions and potentially landslides.

In order to clarify and eventually update the information provided by the databases, it was decided to look for observation details in the available literature and to analyse, when possible, the recorded signals of the five coastal gauges located in Vanuatu (Table 1). This exercise could also potentially highlight additional events, and especially non-seismic/volcanic events.

Firstly, the methodology proposed by Roger et al. (2019) using a decision table has been applied to identify the earthquakes potentially having been able to trigger a tsunami recorded in Vanuatu. From the results obtained using this decision table, automatic extraction of signal periods corresponding to 2 hours before and 24 hours after the earthquake and de-tiding using a polynomial function have been performed. Then, visual check of the resulting extractions of signal has been done to identify tsunami waveforms from the background noise.

The same process has been run for known volcanic crisis form Vanuatu Arc volcanoes.

Finally, a global check of the whole signal has been done to eventually identify non-seismic/volcanic sources.

The detailed list of the different tsunamis reported or recorded in Vanuatu Arc for a time period running from August 1863 to 30 June 2023 is presented in Table S1. Significant events are presented hereafter in section 3.2.

3. Catalogue

3.1 Description

The list of tsunamis being reported and/or recorded in the Vanuatu Arc is composed of one hundred (100) events detailed in Table S1. Fifteen (15) of them show a maximum recorded amplitude on gauge, or a run-up value of one meter and above, including seven (7) showing a run-up value of more than three (3) meters. Eight (8) of them show a maximum amplitude on gauge, or a run-up value of between 0.3 and 1 m. Sixty-two (62) show a maximum amplitude on gauge, or a run-up value of less than 0.3 m. Neither amplitude value nor run-up value was found reported for fourteen (15) events.

If most of the tsunamis listed herein are associated to earthquakes (92), eight (8) show different generation mode. Three (3) events are either due to volcanic activity or an earthquake (no certainty about the source). Four (4) events are related to volcanic eruptions, including the Karua (1901), the Hunga Tonga-Hunga Ha'apai (2022) and the East Epi (1958, 2023) volcanic eruptions. And one (1) event recorded on LITZ on 16 November 2021 could be attributable to volcanic activity at Gaua Volcano.

The three largest amplitudes recorded at a tide gauge correspond to 1.4 m on Lenakel following the 2021 Mw 7.7 Matthew Island earthquake, 1.37 m on LATA following the 2011 Mw 9.1 Tōhoku (Japan) earthquake, and 1.03 m on VANU following the HTHH (2022) volcanic eruption. Maximum amplitudes of 0.8 m and 0.7 m were recorded on LATA following the 2013 Mw 8.0 Ndende earthquake and LENA following the 2023 Mw 7.7 southeast Loyalty Islands earthquake, respectively.

The two largest reported run-ups are 17 m at Port-Resolution, Tanna Island, on 10 January 1878 (Soloviev and Go, 1974), and 11 m at west Ndende, Eastern Solomon Islands, on 6 February 2013 (Fritz et al., 2013).

Figure 2 shows the maximum wave amplitude or elevation run-up either reported or recorded on coastal gauges as a function of time. It shows that small tsunamis occur relatively frequently (62 in ~30 years) while larger ones posing a direct threat to people (> 30 cm) are less frequent (23 in ~150 years). It is important to note that this number could be larger if the 15 events for which there is no amplitude or run-up data available were showing amplitude or run-up elevation above 1 m. This may be the case for most of them to be reported in coeval documents. Figure 2 also shows the tsunami intensity I as a function of the maximum wave amplitude (or elevation run-up in our case) H_{max} based on Iida (1963) scale, also called Imamura-Iida scale (Gusiakov, 2009):

$$I = \log_2 H_{max}$$

Note that only one event shows an intensity I=4 or more for the Vanuatu Arc region.

As most of the tsunamis recorded/reported in the Vanuatu Arc are triggered by earthquakes, it is interesting to show the dependency of the tsunami amplitude on the earthquake magnitude. However, it does not allow to draw any clear trend as shown on Figure 3.

Tsunamis reported or recorded in the Vanuatu Arc have multiple origins as presented on Figure 4: they can be triggered by earthquakes all around the Pacific Ocean Ring of Fire, especially in southwest America or Japan (Figure 4a), or regionally by earthquakes and/or volcanoes occurring at the subduction zones in the southwest Pacific Ocean (Figure 4b), but most of them are triggered by seismic or volcanic activity locally due to the Vanuatu Subduction Zone processes (Figure 4c).

3.2 Description of events

Notice to reader: for the oldest references, the authors directly rely on the information reported in (a) Soloviev and Go (1974) for the period 1863-1967 and (b) Louat and Baldassari (1989) for the period 1729-1989, i.e., Inglis (1887) (in b), Roberston (1892) (in b), Wawn (1893) (in b), Paton (1894) (in b), Davillé (1894) (in a and b), Mawson (1905) (in b), Bourge (1906) (in a and b), O'Reilly (1956) (in b), Rothé (1966) (in a), Carney and Campillo (1980) (in b), but in the following, the original references are indicated. Times are indicated either local (LT) or universal (UTC).

3.2.1 Tsunamis of particular interest from local events with observations data

- 28-30 March 1875 (Aneityum, Aniwa, Erromango)

A huge seismic crisis felt both in the Loyalty Islands in New Caledonia and in the southern Vanuatu Islands began the 28 March in the southern portion of the VSZ. Major shocks occurred the 28 and the 30 March and were followed by "tidal wave" as reported by Soloviev and Go (1974) and Louat and Baldassari (1989). The first event, deadly in Lifou, Loyalty Islands, New Caledonia, was also severely felt in Aneityum, the southernmost Vanuatu inhabited Island. On Aneityum one person drowned, and others were severely hurt (Inglis, 1887, in Louat and Baldassari, 1989). The sea rose around the whole island and did serious damage to dwellings and crops (Inglis, 1887). A wave of 10-11 feet (~3 m) above the spring-tides level arriving 15 minutes after the earthquake is reported (Inglis, 1887). Based on testimonies from the Loyalty Islands and numerical modelling, the magnitude of the 28 March 1875 earthquake is estimated to 8.1-8.2 (Ioualalen et al., 2017). The earthquake and tsunami were also felt on Erromango (Roberston, 1892) and Aniwa (Paton, 1894). On both islands a "tidal wave" from the second 30 March event was higher than the 28 March one.

At Erromango, Roberston (1892) indicates to see “a prodigious wall of sea, stretching right across the bay, and which appeared about forty feet high” (~12 m). However, considering the described damages, this value is considered to be overestimated herein.

- January/February/August 1878 (Tanna Volcano)

On the year 1878, several earthquakes and tsunamis associated with eruption(s) of the Mount Yasur Volcano (Tanna Island) drastically changed the hydrography of Port Resolution on the southeastern coast of Tanna Island (Patton, 1894; Mawson, 1905; Bourge, 1906; Soloviev and Go, 1974; Louat and Baldassari, 1989). On 10 January a strong earthquake generated a 6 m uplift of the coast and a local devastating tsunami rising 12 m above highest tide mark (or 15-17m high from other sources according to Soloviev and Go, 1974). On 11 February there was an even stronger shock generating a large sea wave and causing local uplift of 12 m and collapse into the sea of other parts of the coast. A third main shock occurred in August and again changed the morphology, raising part of the bottom of the harbor above sea level. The total uplift of the shoreline of 15 m in 1878 and the extraordinarily uplift rate (156 mm/y between AD 1009 and AD 1992) of the Yenkahe resurgent block located in a partially submerged Quaternary caldera is likely associated with the movement of magma below (Chen et al., 1995).

- October 1883, after the 3rd (Southwest Malekula)

Following an earthquake, three tidal waves swept the south-western coast of Malekula from westward. The amplitude of the tsunami was about 2 m (14 feet from trough to crest) (Wawn, 1893 in Louat and Baldassari, 1989). The eyewitness W.T. Wawn who was on board a ship anchored in the channel between Ura Islet and the south-western coast of Malekula, well described the scene which is reported below: “*At either side, on the shallow reefs, and high over the low bushes and smaller trees that lined the shore, a huge wave was breaking, sweeping steadily along the coast from westward, until it disappeared beyond a long, low point of land. It was the swell of this wave, unbroken in the deeper water, which had caught the ship aft, and had slewed her round to her anchor. On the islet we could hear the yells and cries of the natives, as they fled from an adjacent village, making for higher ground. On the main island, cloud of dust could be seen for miles away, showing where landslips has occurred on the side of the steep hills and mountains. For miles the whole surface of the earth had subsided, sinking eight feet or so, which had caused the great wave to rush into the deepened channel. Then, slowly and gradually, came an upheaval. The water poured out from the flooded forest, bearing with them portions of the huts of the savages, canoes, trees and branches, and even two or three squeaking pigs, cascading over the face of the flat shore-reefs. These now rose as high above their normal position as they had before sunk below it, forming flat terraces along the coasts, which were elevated to six feet above the surface of the sea. Masses of "Live" coral showed along the face of the raised shore-reefs, displaying brilliant hues, blue, green, yellow, purple, and red, all shining and glistening in the sun. This was the first act. A pause of a minute followed. Then, gradually and majestically, the upraised coral sank again, and the bright colour disappeared. Then came another subsidence, and a second vast billow rolled in from westward, making our chain rip and tear at the bows as if it meant to pull the windlass out of the ship. Breaking into clouds of foam, the wave ran roaring along the shores, while every here and there some huge tree came toppling over, with torn root or broken trunk. The second upheaval was not equal to the first; the reefs did not rise more than about three feet above the water. Though a third wave rolled in, it was only a* *"piccaninny" (small) when compared with those that had preceded it. When the earthquake was over, I could perceive no difference in the height of the shore, from the level of the sea. The only effect remaining visible were the branches and broken trees floating about, or lying strewn along the beaches, with here and there, a bare yellow brown patch on the side of the hill...*"

- 24 July 1961 (23 July UTC) (Efate)

During a seismic swarm located south of Efate, a Mw 7.3 earthquake was severely felt (Intensity VI on Mercalli scale) on the islands of Efate and Erromango, and also (Intensity IV) on Tanna, Malekula, Epi and the Loyalty Islands. Ten to 15 minutes after the shock, a tsunami with 1 to 1.5 m of vertical oscillations and a period of about 12 minutes, generating minor damage, was reported in Port Vila and Forari (Efate Island) (Soloviev and Go, 1974; Louat and Baldassari, 1989).

- 12-13 August 1965 LT (11-13 August UTC) (Northern Malekula, Southern Santo)

A seismic swarm with several strong shocks (Mw 7.2 to 7.6) occurred between Malekula and Santo between 11 and 13 August (see Ebel, 1980). They were felt with estimated intensity of VII to VIII on the Mercalli scale at Norsup (North Malekula) and Luganville (South Santo). Three large earthquakes on the 11 and 12 August (UTC) generated many damages, landslides, collapses on Santo and Malekula. The main event (Mw 7.6 at 22:31 the 11 August UTC) caused an uplift of the northwestern part of Malekula of 0.5 to 0.8 m according to Benoit and Dubois (1971), and up to 1.2 m according to Taylor et al. (1980). The shock generated a tsunami which rose with a height of 7 m in some bays of Malekula (according to Rothé, 1966, in Soloviev and Go, 1974). The height of the tsunami was reported at 2.5 m on Tongoa Island and 1.2 m at Port Vila, Efate (Soloviev and Go, 1974). However, a small tsunami is indicated in other studies (Benoit,1965, in Louat and Baldassari, 1989), and Benoit and Dubois (1971) stated that there was no tsunami associated with the main shocks. In contrast, the main aftershock on 13 August (Mw 7.4 at 12:40 UTC) was followed by a 2 m-high tsunami which caused loss of small ships on the west coast of Santo, and destruction of coastal installations (Benoit and Dubois, 1971). The information provided by Benoit and Dubois (1971) who surveyed the islands after the event is considered herein. A school of Malo Island was also partly flooded by a tsunami on 13 August at 14:00 (UTC) (Louat and Baldassari, 1989).

- 1 January 1967 LT (31 December1966 UTC) (Vanikoro)

A large earthquake (Mw 7.8) was severely felt on Vanikoro Island, easternmost Solomon Islands Province, and caused avalanches and tsunami within the lagoon, with 2 m-high waves (Soloviev and Go, 1974). A tsunami was recorded at Suva (Fiji) and Pago Pago (American Samoa). A large aftershock (Mw 7.1) generated also a tsunami in the lagoon with an amplitude of 0.8 m (Soloviev and Go, 1974).

- 17 May 1995 LT (16 May 1995 UTC) (south Vanuatu, south-east of Walpole Island)

A large normal fault-type earthquake (Mw 7.7), located southeast of Walpole Island on the plunging plate at the southernmost part of the VSZ, generated a tsunami which arose 8 m at Aneityum and 1.5 m at Erakor island in Port Vila on Efate (Lardy, 1995). At Erakor the water rose at the entrance of the bungalows and stayed at high level for 10-15 minutes.

- 21 April 1997 (Torres)

A large Mw 7.8 thrust-type earthquake occurred north of Torres Island (Northern Vanuatu) and caused a local tsunami on the east of Hiu Island with run-up elevation as high as 3 m and generated a co-seismic subsidence of at least 0.5 m on the northern part of the Loh Island (Kaverina et al., 1998; Ballu et al., 2011). The tsunami height recorded at Port Vila, Funafuti and Suva tide gauge stations are 20, 10 and 10 cm respectively.

- 26 November 1999 (East Ambrym- South Pentecost)

On 26 November 1999 a Mw 7.5 thrust-type earthquake occurred East of Ambrym Island on the back-arc compressive zone of central Vanuatu (Pelletier et al., 2000; Lagabrielle et al., 2003; Régnier et al., 2003). It is the largest known event on the Vanuatu back-arc. It caused an uplift (up to 1.5 m) on the easternmost tip of Ambrym (Pelletier et al., 2000) and triggered a destructive tsunami affecting the South Pentecost and east Ambrym Islands shorelines, as well as more distant islands as Malekula and Efate, killing 5 people and fully destroying the village of Martelli Bay on South Pentecost (Caminade et al., 2000). Run-up heights reached 6-7 m above sea level in Martelli Bay on South Pentecost (Caminade et al., 2000) and at Pamal Rivermouth in East Ambrym (Pelletier et al., 2000). Tsunami modelling results are in good agreement with reported near field run-ups (Ioualalen et al., 2006). Run-up of 1.8 m at the eastern shore of Malekuka caused the sinking of a 50-tons wooden ship. Run-up heights on Efate, although far from the source, locally exceeded 1.5 m and reached 2.6 m on the northern shore (Caminade et al., 2000). Tide gauge at Port Vila recorded a maximum tsunami wave amplitude of 32 cm, half an hour after the earthquake (Figure 5).

- 3 January 2002 LT (2 January 2002 UTC) (Efate)

A significant event of magnitude Mw 7.2, located West of Efate Island and felt on the whole island, caused some damages in the capital city Port Vila, and generated a tsunami which arrived 15 min after the shock in the bay of Port Vila. Maximum amplitude of 32 cm is recorded at the Port Vila tide gauge. However, eyewitnesses reported a much larger effect at different places around the harbour, with maximum wave heights to around 3 m from trough to crest) (Shorten, 2002). According to the same reference, a small tsunami following a large Mw 6.4 aftershock is also reported although nothing can be seen on the tide gauge record.

- 7 October 2009 UTC (Vanikoro)

A seismic crisis with 3 large events showing magnitudes from Mw 7.4 to Mw 7.8 occurred southwest of Vanikoro and caused a tsunami which was recorded on the Port Vila tide gauge (30 cm). No additional information about the event was reported and no investigation was led in the closest islands from the source (i.e., Vanikoro and Torres Islands). Note that in Table S1, only one tsunami is reported according to the gauge record analysis, but this one is associated to the two largest earthquakes (Mw 7.7 and 7.8).

- 6 February 2013 (Santa Cruz)

This is one of the largest (Mw 8.0) known earthquakes having occurred along the VSZ, west of Ndende Island in the Santa Cruz Islands group, the easternmost province of the Solomon Islands (Lay et al. 2013; Romano et al, 2015). It generated a deadly tsunami which struck the Ndende Island, in particular the western part of the island with a maximum height of about 11 m and local flow depths above ground of 7 m (Fritz et al., 2013). The same authors reported that the tsunami killed 10 people, injured 15 and destroyed or damaged ~1000 houses. An amplitude of ~0.9 m was recorded on the tide gauge at the wharf of Lata, the main city of Ndende (Figure 6). The tsunami was also recorded at DART stations and coastal tide gauges throughout the Pacific. Port Vila tide gauge recorded a maximum tsunami amplitude of 33 cm (Table S1).

- 5 December 2018 (Southern Vanuatu, southeast of Mare, Loyalty Islands)

On 5 December 2018, a Mw 7.5 thrust-type earthquake occurred southeast of Maré, Loyalty Islands, in the region where the Loyalty Ridge enters the trench and is subducting/colliding with the Vanuatu arc. Widely felt in Vanuatu and New Caledonia, the shaking was quickly followed by a tsunami as detailed by Roger et al. (2019, 2021). Maximum run-up of ~4 m was reported along the southern coast of Aneityum Island, the southernmost island of Vanuatu.

- 10 February 2021 (Matthew Island, southernmost islands group of the VSZ)

On 10 February 2021, a powerful Mw 7.7 thrust-type earthquake occurred at the southeasternmost part of the VSZ, south of Matthew and Hunter Islands, and generated a tsunami which was observed on most coastal gauges and DART stations in the southwest Pacific region as far as Tasmania to the south and Tuvalu to the north at distances of 3,000 and 1,800 km from the epicentre, respectively (detailed in Gusman et al., 2022a; Roger et al., 2023a). The maximum amplitude of about 1.4 m was recorded on the closest tide gauge at Lenakel on Tanna Island, southern Vanuatu.

- 31 January 2023 (East Epi volcano eruption)

Between the 25th and the 31st of January 2023 (UTC), an eruption occurred at one of the East-Epi submarine volcanoes. The eruption evolved to surtseyan on the 31st and was followed by a small tsunami showing amplitude of ~5 cm recorded on the coastal tide gauges of Port Vila to the South and Luganville to the North located at distances of 125 and 175 km from the eruption area, respectively (Roger et al., 2023b).

- 19 May 2023 (Southeast of Walpole Island, Loyalty Islands)

On 19 May 2023, a Mw 7.7 earthquake, located southeast of Walpole Island, at almost the same place but with a comparable focal mechanism solution that the one of the 17 May 1995 event (slightly different in terms of azimuth and non-double couple component), i.e. a normal fault-type event on the Australian plunging plate at the outer wall of the southernmost part of the VSZ, generated a small tsunami which was recorded on the tide gauges of New Caledonia, Vanuatu and northern New Zealand. The largest wave has been recorded at the Lenakel tide gauge on Tanna showing a maximum amplitude of 70 cm. Note that this tide gauge stopped transmitting data afterwards.

3.2.2 Tsunamis from far field and regional origin with observation data

Since the establishment of the 6-min sampling rate tide gauge in Port Vila in 1993 and then at the three other locations in Vanuatu, tsunamis from far field and regional origin can be recorded.

a) Far field origin

4 October 1994 Mw 8.3 Shikotan (Kuril Islands)-Hokkaido (Japan), 10 June 1996 Mw 7.9 (Alaska), 23 June 2001 Mw 8.4 southern Peru, 26 December 2004 Mw 9.1 (Sumatra), 15 November 2006 Mw 8.3 (Kuriles), 27 February 2010 Mw 8.8 Maule (Chile), 11 March 2011 Mw 9.1 Tōhoku (Japan), 1 April 2014 Mw 8.2 Iquique (Chile), 16 September 2015 Mw 8.3 Illapel (Chile), and the 8 September 2017 Mw 8.2 Chiapas (Mexico).

All these recent widespread trans-pacific tsunamis, recorded on most of the gauges of the Pacific Ocean, were registered on the gauges in the Vanuatu Arc. For instance, on Port Vila tide gauge, the "Maule" tsunami perturbated the sea-level in the harbour where the gauge is located during more than 2 days following the first arrival of the tsunami on 27 February 2010 showing a maximum amplitude of ~0.3 m (Figure 7). The Tōhoku tsunami arrived at Port Vila ~8 h after the main earthquake on 11 March 2011 showing a maximum height of ~0.7 m (Figure 7) and perturbating the harbour during more than 3 days. This was also the case for the 2004 global transoceanic "Indian Ocean" tsunami, which reached the Port Vila tide gauge after ~21 h of propagation, showing a maximum height of ~0.1 m (Figure 7) and perturbating the harbour during more than 4 days.

b) Regional origin

16 November 2000 Mw 8.0 Rabaul (Papua New Guinea), 1 April 2007 Mw 8.1 Gizo (New Georgia Islands Group, Solomon Islands), 23 December 2004 Mw 8.1 Macquarie, 29 September 2009 Mw 8.1 Samoa-North Tonga, 5 March 2021 Mw 8.1 Kermadec, 15 January 2022 HungaTonga Hunga Ha'apai eruption (Tonga).

The recent and major tsunamis of regional origin have been also recorded on the Vanuatu Arc tide gauges (see the list above) excepted the 17 July 1998 Aitape (Papua New Guinea) deadly tsunami, which is supposed to be mainly caused by a submarine slump triggered by the shaking of the initial Mw 7.0 earthquake (Synolakis et al., 2002).

On 5 March 2021, 3 earthquakes of magnitude Mw 7.3, 7.4 and 8.1 respectively occurred on the Hikurangi-Kermadec subduction zone and triggered 3 distinct tsunamis recorded on coastal gauges and DART stations of the southwest Pacific. The third one had a wider impact, being recorded in many places across the Pacific Ocean, and some locations in the Atlantic and Indian Oceans (Roger, 2023). It was clearly recorded in Vanuatu at LENA, VANU and LITZ coastal gauges with a maximum amplitude of 38 cm at LENA.

The widespread tsunami triggered by the 15 January 2022 eruption of the Hunga Tonga-Hunga Ha'apai volcano was well recorded in the southwest Pacific Region (e.g., Gusman et al. (2022b)), and particularly on the Vanuatu tide gauges VANU, LITZ and LUGA where it reached amplitudes of 0.5 m and more as shown on Figure 8.

3.2.3 Tsunamis reported without details (black events in Table 1 and Figure 1)

- 17 August 1863 (LT) (Erromango, Tanna)

The oldest known tsunami reported in Vanuatu occurred on 17 August 1863 (Soloviev and Go, 1974). Following a shock felt in New Caledonia, most strongly at Kanala and Vagap (Poindimié) on the east coast of Grande Terre, the schooner "Ariel", passing Port de France (former name for Nouméa before 1966) on 26 August 1863, reported that a shock on 17 August was also felt on Erromango Island and was accompanied by a large wave which must have done great damage on land. Another schooner which was close to Tanna Island reported that the shock may have related to an eruption of Yasur Volcano on Tanna Island.

- August 1892, first week, about 0:20 (LT) (Santo)

There was a very strong shock felt at Luganville, Santo Island. An eyewitness, Davillé, who was sleeping on the top deck of a small schooner at Shark Bay, on the east coast of Santo, woke up and saw that a gigantic foaming roller had suddenly appeared on the hitherto calm sea surface and was advancing toward the schooner from south to north (Davillé, 1894, in Soloviev and Go, 1974; and in Louat and Baldassari, 1989).

- 27 August 1893 (LT) (Efate)

A wave crossed the bay of Port Vila and reached the coffee shop of the French merchant company (Davillé, 1894, in Soloviev and Go, 1974; and in Louat and Baldassari, 1989).

- 8 August 1901 (LT) (Karua, southeast Epi)

A tsunami followed an eruption of a volcano near Epi Island on 8 August 1901 as described by testimonies reported in the Sydney Morning Herald (1901): "*The eruption was followed by a tidal wave, which did infinitely greater damage to the plantations than the eruption.*" The responsible volcano is likely to be the Karua, located southeast of Epi Island, which is known to be very active in 1900-1901 (Eissen et al., 1991).

- 19-20 November 1933 (LT) (Malekula)

Earthquakes were felt on Malekula Island. One of them, on 19 November, was strong enough to damage the church and other buildings at Lamap, southern Malekula. Following these shocks, the southern coast of Makekula, at least from Assouk to Port

Ravallec, subsided of about 0.3-0.4 m. It is also reported that the subsidence was accompanied with a slight tsunami (Louat and Baldassari, 1989).

- 3-4 December 1950 (LT) (Southwest Efate)

Following a seismic crisis felt in Port Vila (22 shocks in 24 hours) including a large Mw 7.9 earthquake on 2 December 1950 at 19:52 UTC located south-west of Efate, west-north-west of Erromango, a tsunami is reported from Erakor Island, Port Vila (O'Reilly, 1956, in Louat and Baldassari, 1989).

- 7 October 1958 (LT) (East Epi)

Unusual waves reported by locals on the southeast of Epi Island seemed to be caused by an underwater volcanic eruption (Soloviev and Go, 1974). Airplane survey of the region by the French naval aviation on 7 October 1958 around 10:00 LT revealed spots and streams of discoloured water on the so called "Epi B" underwater volcano, as well as bubbling of water above the submarine Karua Volcano located on the Kuwae Caldera (sketch of Brossard, 1958, in Soloviev and Go, 1974). Further aircraft surveys on 18 November (Lt. Valette) and December 16 (R. Priam) reported the same manifestations but with less intensity (Eissen et al., 1991).

- 13 May 1980 (LT) (12 May 1980 16:37 UTC) (Mere Lava)

A Mw 6.1 earthquake, located east of Mere Lava Island (Banks Islands Group) and felt with intensity V-VI on the island, caused a small tsunami attested by the stranding of fishes on the shore near the Tasmat village, as reported by Father Langon in Carney and Campillo (1980) in Louat and Baldassari (1989).

- 9 and 18 July 1980 (LT) (Torres)

Following large thrust fault-type earthquakes (Mw 7.5 the 8 July at 23:19 UTC and Mw 7.9 the 17 July at 19:42 UTC) occurring north of Torres Islands. Run-up height of less than 2 m is reported in Lockridge and Smith (1984) without more details including location precision. Slight tsunami waves have been reported at the tide gauge of Port Vila (Carney and Campillo 1980, in Louat and Baldassari 1989). As previously indicated, the tide gauge data of Port Vila from this period seems no more available.

3.3 Potential tsunamis from debated local events

- 1452 AD Kuwae eruption (tsunami from volcanic eruption)

The Vanuatu Arc, showing several aerial and submarine explosive-type active volcanoes with steep slopes, can be seen as a strong candidate to produce volcanism-triggered tsunamis. Destructive tsunami is reported to be associated to the eruption of Yasur Volcano on Tanna Island in 1878 and tsunamis related with the eruption of East Epi Volcano were reported in October 1958 and recorded in January 2023 (Roger et al., 2023b).

The large (12 km x 6 km) Kuwae submarine caldera located between Tongoa and Epi Islands is considered to be the result of a gigantic eruption in the mid-15 century (Monzier et al., 1994; Witter and Self, 2007). This cataclysm which literally broke the former Kuwae volcano and separated all the neighbouring islands in their present distribution is widely reported in the Vanuatu oral tradition and several kastom stories and may have caused a large destructive tsunami. However, excepted the preliminary work of Goff et al. (2008), the potential sedimentary deposits of this major event were not searched so far.

- Tsunami from landslide?

Several reported particular waves or abnormal movements of the sea not associated to any earthquakes may have been triggered by local landslide. Indeed, such events caused by underwater or subaerial landslides may have likely occurred along the VSZ. This could be the case for: the event on 13 March 1959 which destroyed the catholic mission at Loanatom, Tanna Island (Wallez, 1998), the tsunami on 28 November 1966 at 13:00 LT in Mohawk Bay, Santa Cruz Islands (Soloviev and Go, 1974), and the event on 10 July 1993 at Whitesands, southern coast of Efate Island (testimony collected by ORSTOM and reported in Wallez, 1998).

3.4 Tsunamis not reported in Vanuatu but elsewhere around – not in the catalogue

- Local and regional tsunamis

Some tsunamis triggered by local earthquakes along the VSZ and regional events from the Solomon Subduction Zone (Mw 8.1 shock on 21 September 1920 LT west of Aneityum Island, Mw 7.8 on 4 October 1931 LT southwest of San Cristobal Island, Mw 7.7 on 19 July 1934 LT west-south-west of Vanikoro island, Mw 7.3 on 21 July 1934 southwest of Ndende Island) and reported in other neighbouring locations, for example in New Caledonia (Soloviev and Go, 1974; Sahal et al., 2010), have not been reported in the Vanuatu Arc islands. This raises the question in particular for the largest event ever recorded in Vanuatu since 1900, i.e. the Mw 8.1 earthquake on 20 September 1920 UTC which went unnoticed in Vanuatu and almost unnoticed in New Caledonia (Louat and Baldassari, 1989) and for which a tsunami has been reported four hours and thirty minutes later on Apia, Samoa (Soloviev and Go, 1974). Estimated local run-up of 2 to 6 m is indicated in Lockridge and Smith (1984). However, no run-up has been reported anywhere. Based on the lack of testimony (excepted one in Ouvéa Island, New Caledonia, reported by Sahal et al, 2010) and numerical modelling, the magnitude of this event is estimated to 7.5-7.8 instead 8.1 (Ioualalen et al., 2017).

- Transoceanic tsunamis

Like for local and regional events, the widespread trans-pacific tsunamis, generated by the 4 November 1952 Mw 9.0 Kamtchatka earthquake or by the 22 May 1960 Mw 9.5 Chile earthquake, have not been reported in Vanuatu although they were documented, for what concerns the Chile event, in New Caledonia (Sahal et al., 2010) and in other countries of the southwest Pacific Region, i.e. Fiji, New Zealand and Australia.

4. Discussion

4.1 About the catalogue and the knowledge of the tsunami hazard

This list of tsunamis shows that Vanuatu and Eastern Solomon Islands are exposed to this natural hazard. One hundred tsunamis have been identified since 1863, and 78 since 1993 when sampling rate at tide gauge was setup high enough to record small ones. Tsunami sources are local, regional and distant (far-field tsunamis). Tsunamis from local origin show the largest amplitude and/or run-up, except the 2011 Tōhoku tsunami which is one of the largest tsunamis recorded/reported in the Vanuatu Arc. Only 7 of them show run-up value higher than 3 meters and 3 have been deadly: at least 1 drowned man on Aneityum following the large 1875 earthquake, 5 victims on South Pentecost following the 1999 Mw 7.5 east Ambrym earthquake and 10 fatalities on west Ndende following the 2013 Mw 8.0 Ndende earthquake. The low number of casualties is likely due to the fact that tsunamis are not very large and highly powerful (maximum earthquake magnitude M ~8), but also chiefly results from a very good knowledge of the tsunami phenomenon, which is orally transmitted between generations, through myths for instance (e.g., Nunn et al., 2006). The good understanding of the tsunami hazard appears quite well in the writings recounting ancient events (like that of 1875) and was clearly pointed by the international tsunami survey teams following the deadly events of 1999 (Caminade et al., 2000) and 2013 (Fritz et al., 2013). However, it is to note that it is always difficult to collect precise testimonies, especially over large regions like the Vanuatu Arc, even for recent events as indicated by Rahmi et al. (2019).

It is important to indicate that there is a lack of knowledge about underwater landslides in Vanuatu, which are known to be able to trigger very localized and potentially large amplitude tsunamis (Roger et al., 2024).

Also, underwater volcanoes are not well-known, and there is a high potential for the existence of active volcanoes especially within a 400 km-long section without aerial active volcano in the northern part of the arc between Vanua Lava (Banks Islands, Vanuatu) and Tinakula (Eastern Solomon Islands).

This study allows to build a tsunami exceedance frequency curve (Figure 9) showing the cumulative rate of tsunamis (per year) exceeding the amplitude or run-up value given by the present tsunami catalogue over the period 1863-2023. A common practice is to fit a simple power law (e.g., $y = 0.0716x^{-0.581}$, shown on Figure 9), which provides a good approximation, except for the largest amplitudes (low exceedance frequency). Using the work from Burroughs and Tebbens (2001) on the fitting of upper-truncated power law to a cumulative dataset proposing the equation of the upper-truncated power law M as $M(r) = C * (r^{-D} - r_T^{-D})$, where r is the object size (the maximum amplitude or run-up in our case), R_T is the maximum size, and C and D are constant values providing the best fit of the upper-truncated power law, we found a best fit with C= 0.0993, D=-0.4626. Visual comparison with the results obtained by Geist and Parsons (2006) for Acapulco tsunamis shows strong similarity with the trend they obtained but with a higher exceedance frequency generally, keeping also in mind that the Vanuatu catalogue is probably not showing all the historical events over the considered period (especially during the non-instrumental period) according to the previous comments, and the number and types of observations are also not representative of all the locations in Vanuatu, which may result in bias and underestimation of the tsunami hazard.

4.2 Improvement of tsunami hazard knowledge

This study clearly demonstrates that there is a lack of both geographic and temporal coverage of records and observations all along the Vanuatu Arc. Only 5 recently installed coastal gauges are disseminated along the approximately 1,500 km-long Vanuatu Arc. Moreover, these gauges were installed for maregraphic purposes (i.e., tide observation and sea-level rise) and are not specifically designed for tsunami recording. In addition, they are not regularly spaced along the arc, they are located in semi-enclosed places (like harbours, or bays) potentially submitted to disturbances triggered by navigation and resonance phenomenon, and sometimes they are not transmitting real-time data.

In 2021, two DART stations have been deployed by New Zealand as part of the New Zealand DART Network (Power et al., 2018) in front of the southern part of the Vanuatu Arc in addition to the Australian one located north-northwest of New Caledonia between the northern part of the Vanuatu Arc and Australia.

Deployment of additional coastal gauges and/or sea-bottom pressure sensors (like DART stations for example) is strongly recommended to collect more tsunami records in order to improve the hazard knowledge in that region. It is to note that a SMART (Science Monitoring And Reliable Telecommunications) cable project is under development between Vanuatu and New Caledonia (Howe et al., 2022). This SMART cable technology provides an additional opportunity to monitor sea-level variations caused by tsunami waves propagation through the integration of pressure sensors amongst other environmental instruments in the system (Howe et al., 2019). Once installed, it will be able to help assess whether a tsunami was triggered by an earthquake or not, complementing the DART systems already operational in the region. It may also allow to detect underwater landslides which are potential tsunami sources. In fact, tsunami sources other than earthquakes like submarine landslides and volcanic eruptions are not well known in the Vanuatu Arc. One of the reasons is the lack of high-resolution bathymetric data around the numerous islands' slopes, and the poor knowledge of the underwater volcanic activity in the region.

Finally, the very limited period of time covered by the present catalogue could be increased via the analysis and precise dating of sediments moved by tsunami waves: paleotsunamis surveys led in suitable environments (e.g., swamp, lagoon, topographic depression, etc.) able to preserve marine submersion footprints for centuries or more.

Acknowledgements

The authors are grateful to Mike Davis (Bureau of Meteorology, Australia) who shared the data for LATA and VANU gauges. This work was supported by GNS Science's Hazards and Risk Management (HRM) science programme funded through the Strategic Science Investment Fund (SSIF).

Data availability

Most of the coastal gauge records used in the present study are publicly available online (http://www.ioc-sealevelmonitoring.org). The other datasets were provided by the Bureau of Meteorology (Australia).

Author contribution

JR organized the study, collected and processed the coastal gauges data, analysed the results, prepared the figures and wrote the manuscript. BP collected and summarized historical documents, and wrote the manuscript. The two authors agreed with the submitted version of the manuscript.

Competing interests

The authors declare no conflict of interest.

References

Aldrich, R.: From the New Hebrides to Vanuatu. In: France and the South Pacific since 1940. Palgrave Macmillan, London. https://doi.org/10.1007/978-1-349-10828-2_6, 1993.

Ballu, V., Bouin, M-N., Siméoni, P., Crawford C., Calmant S., Kanas T., Boré J.-M., and Pelletier B.: Comparing the role of absolute sea-level rise and vertical tectonic motions in coastal flooding, Torres Islands (Vanuatu). Proceedings of the National Academy of Sciences. 108(32): 13019-13022, 2011.

Bedford, S., Spriggs, M., and Regenvanu, R.: The Teouma Lapita site and the early human settlement of the Pacific Islands, Antiquity 80, 812-828, https://doi.org/10.1017/S0003598X00094448, 2006.

Bedford, S., Spriggs, M., Regenvanu, R., Macgregor, C., Kuautonga, T., and Sietz, M.: The excavation, conservation and reconstruction of Lapita burial pots from the Teouma site, Efate, Central Vanuatu, in S. Bedford, C. Sand and S. Connaughton (eds), Oceanic Explorations: Lapita and Western Pacific Settlement, Canberra, Australian National University E Press, Terra Australis 25, 223-240, 2007.

Bedford, S., Hoffman, A., Kaltal, M., Regenvanu, R., and Shing, R.: Dentate-stamped Lapita reappears on Efate, Central Vanuatu: a four decade-long drought is broken. Archaeology in New Zealand, 47(1), 39-49, 2004.

Benoit, M., and J. Dubois: The earthquake swarm in the New Hebrides archipelago, August 1965, Recent Crustal Movements, Roy. SOC. N. Z. Bull., 9, 141-148, 1971.

Burroughs, S.M., and Tebbens, S.F.: Upper-truncated power law distributions. Fractals, 9(02), 209-222, 2001.

Calmant, S., Pelletier, B., Bevis, M., Taylor, F., Lebellegard, P., and Phillips, D.: New insights on the tectonics of the New Hebrides subduction zone based on GPS results, J. Geophys. Res., 108, B6, 145 2319-2340, https://doi.org/10.1029/2001JB000644, 2003.

Caminade, J.P., Charlie, D., Kanoglu, U., Koshimura, S., Matsutomi, H., Moore, A., Ruscher, C., Synolakis, C.E., and Takahashi, T.: Vanuatu earthquake and tsunami cause much damage, few casualties, Eos. Trans. AGU, 81(52), 641, 646– 647, https://doi.org/10.1029/EO081i052p00641-02, 2000.

Carney, J. N., and A. Macfarlane: Geological evidence bearing on the Miocene to Recent structural evolution of the New Hebrides arc, Tectonophysics, 87, 147 – 175. https://doi.org/10.1016/0040-1951(82)90225-6, 1982.

Chen, J.K., Taylor, F.W., Edwards, L., Cheng, H., and Burr, G.S.: Recent emerged reef terraces of the Yenkahe resurgent block: implications for volcanic, landslide and tsunami hazards. The Journal of Geology, 103, 577-590, 1995.

Costa, P.J., Gelfenbaum, G., Dawson, S., La Selle, S., Milne, F., Cascalho, J., Ponte Lira, C., Andrade, C., Freitas, M.C., and Jaffe, B.: The application of microtextural and heavy mineral analysis to discriminate between storm and tsunami deposits. Geological Society, London, Special Publications, 456(1), 167-190, https://doi.org/10.1144/SP456.7, 2018.

Ebel, J.E.: Source processes of the 1965 New Hebrides Islands earthquakes inferred from teleseismic wave forms, Geophys. J. R. Astr. Soc., 63, 381-403, 1980.

Eissen, J.P., Blot, C., and Louat, R.: Chronologie de l'activité volcanique historique de l'arc insulaire des Nouvelles-Hébrides de 1595 à 1991. ORSTOM, Nouméa, Nouvelle-Calédonie, Sciences de la Terre. Géologie Géophysique. Rapport Scientifique et Technique, n°2, 68 pp., 1991.

Friedlaender, J.S., Gentz, F., Green, K., and Merriwether, D.A.: A cautionary tale on ancient migration detection: mitochondrial DNA variation in Santa Cruz Islands, Solomon Islands. Human Biology, 453-471, https://www.jstor.org/stable/41466065, 2002.

Fritz H.M., Papantoniou A., Biukoto L., and Albert G.: The Solomon Islands Tsunami of 6 February 2013 field survey in Santa Cruz Islands. American Geophysical Union, Fall Meeting 2013, NH41A-1696, 2013.

Geist, E.L., and Parsons, T.: Probabilistic Analysis of Tsunami Hazards. Nat Hazards 37, 277–314. https://doi.org/10.1007/s11069-005-4646-z, 2006.

Goff J., Douglas C., Haruel, C., and Bonte-Grapentin, M.: Preliminary findings of the geology evidences and oral history of tsunamis in Vanuatu. SOPAC Report, 416, 49 p., 2008.

Green, R.C.: A reappraisal of the dating for some Lapita sites in the Reef/Santa Cruz Group of the Southeast Solomons. The Journal of the Polynesian Society, 100(2), 197-207, 1991.

Gusiakov, V.K.: Tsunami history: recorded. The sea, 15, 23-53, 2009.

Gusman, A.R., Roger, J., Power, W., Fry, B., and Kaneko, Y.: The 2021 Loyalty Island earthquake (Mw 7.7): tsunami waveform inversion and implications for tsunami forecasting for New Zealand, Earth Space Sci., 9, e2022EA002346, https://doi.org/10.1029/2022EA002346, 2022a.

Gusman A.R., Roger J., Noble C., Wang X., Power W., and Burbidge D.: The 2022 Hunga Tonga-Hunga Ha'apai Volcano Air-Wave Generated Tsunami. Pure Appl. Geophys. 179 (2022), 3511–3525. https://doi.org/10.1007/s00024-022-03154-1, 2022b.

Hilliard, D.: Colonialism and Christianity: The Melanesian mission in the Solomon Islands. The Journal of Pacific History, 9(1), 93-116, https://doi.org/10.1080/00223347408572247, 1974.

Howe, B. M., Angove, M., Aucan, J., et al.: SMART subsea cables for observing the earth and ocean, mitigating environmental hazards, and supporting the blue economy. Frontiers in Earth Science, 9, 775544, https://doi.org/10.3389/feart.2021.775544, 2022.

Howe, B. M., Arbic, B. K., Aucan, J., et al.: SMART cables for observing the global ocean: science and implementation. Frontiers in Marine Science, 6, 424, https://doi.org/10.3389/fmars.2019.00424, 2019.

Iida, K., 1963. Magnitude, energy and generation mechanisms of tsunamis and a catalogue ofearthquakes associated with tsunamis. Proc. Tsunami Meeting, 10th Pacific Sci. Congress, 1961,IUGG Monograph, 24, 7-18.

Ioualalen, M., Pelletier, B., Watts, P., and Regnier, M.: Numerical modeling of the 26 November 1999 Vanuatu tsunami. Journal of Geophysical Research, Oceans, 111, C6, https://doi.org/10.1029/2005JC003249, 2006.

Ioualalen, M., Pelletier, B., and Solis Gordillo, G.: Investigating the March 28th 1875 and the September 20th 1920 earthquakes/ tsunamis of the Southern Vanuatu arc, offshore Loyalty Islands, New Caledonia, Tectonophysics, 709, 20–38, https://doi.org/10.1016/j.tecto.2017.05.006, 2017.

Kaverina, A., Dreger, D., and Antolik, M.: Source process of the 21 April, 1997 Santa Cruz Island earthquake (Mw 7.8). Geophys Res .Lett., 25 (21), 4027-4030, https://doi.org/10.1029/1998GL900017, 1998.

Kirch, P.V., and Swift, J.A.: New AMS radiocarbon dates and a re-evaluation of the cultural sequence of Tikopia Island, Southeast Solomon Islands. The Journal of the Polynesian Society, 313-336, https://www.jstor.org/stable/26451664, 2017.

Lagabrielle, Y., Pelletier, B., Cabioch, G., Regnier, M., and Calmant, S.: Coseismic and long-term vertical displacement due to back arc shortening, central Vanuatu: Offshore and onshore data following the Mw 7.5, 26 November 1999 Ambrym earthquake. Journal of Geophysical Research, 108(B11), 2519, https://doi.org/10.1029/2002JB002083, 2003.

Lardy M.: Quelques remarques à propos du séisme et tsunami du 17 mai 1995 à Port Vila. Note ORSTOM Port-Vila du 29 mai 1995, 1995.

Lay, T., Ye, L., Kanamori, H., Yamazaki, Y., Cheung, K. F., and Ammon, C. J.: The February 6, 2013 Mw 8.0 Santa Cruz Islands earthquake and tsunami, Tectonophysics, 608, 1109–1121, https://doi.org/10.1016/j.tecto.2013.07.001, 2013.

Lockridge P.A. and Smith R.H.: Tsunamis in the Pacific basin, 1900 - 1983, Map. National Geophysical Data Center, Boulder, Colorado, 1984.

Louat, R., and Baldassari, C.: Chronologie des séismes et des tsunamis ressentis dans la région Vanuatu Nouvelle-Calédonie (1729-1989). ORSTOM, Nouméa, Nouvelle-Calédonie, Sciences de la Terre. Géologie Géophysique. Rapport Scientifique et Technique, N°1, 46 pp., 1989.

Monzier, M., Robin, C., and Eissen, J.-P.: Kuwae (~1425 A.D.): the forgotten caldera. J Volcanol Geotherm Res., 59, 207–218, 1994.

National Geophysical Data Center / World Data Service: NCEI/WDS Global Historical Tsunami Database. NOAA National Centers for Environmental Information. https://doi.org/10.7289/V5PN93H7 [Last accessed on 06/09/2023].

Nunn, P. D., Heorake, T., Tegu, E. T., Oloni, B., Simeon, K. A., Wini, L., Usuramo, S., and Geraghty, P.: Geohazards revealed by myths in the Pacific: a study of islands that have disappeared in Solomon Islands. South Pacific Studies, 27(1), 37-49, http://repository.usp.ac.fj/id/eprint/4023, 2006.

Pelletier, B., Calmant, S., and Pillet, R.: Current tectonics of the Tonga-New Hebrides region, Earth Planet. Sc. Lett., 164, 263–276, 1998.

Pelletier B., Regnier M., Calmant S., Pillet R., Cabioch G., Lagabrielle Y., Bore J.-M., Caminade J.-P., Cristopher I., and Temakon S. : Le séisme d'Ambrym-Pentecôte (Vanuatu) du 26 novembre 1999: données préliminaires sur la séismicité, le tsunami et les déplacements associés. C. R. Acad. Sci. Paris, Science de la terre et des planètes, 331, 21-28 https://doi.org/10.1016/S1251-8050(00)01382-3, 2000.

Petchey, F., Spriggs, M., Bedford, S., Valentin, F., and Buckley, H.: Radiocarbon dating of burials from the Teouma Lapita cemetery, Efate, Vanuatu. Journal of Archaeological Science, 50, 227-242, https://doi.org/10.1016/j.jas.2014.07.002, 2014.

Power, W.L., Fry, B., Gusman, A.R., Burbidge, D.R., Brewer, M., and Wang, X.: DART buoys network design. GNS Science consultancy report 2018/147. 53 p. https://www.gns.cri.nz/research-projects/dart-deep-ocean-assessment-and-reporting-of-tsunami/, 2018.

Rahmi, R., Joho, H., and Shirai, T.: An analysis of natural disaster-related information-seeking behavior using temporal stages. Journal of the Association for Information Science and Technology, 70(7), 715-728, https://doi.org/10.1002/asi.24155, 2019.

Regnier, M., Calmant, S., Pelletier, B., Lagabrielle, Y., and Cabioch, G.: The Mw 7.5 1999 Ambrym earthquake, Vanuatu: A back arc intraplate thrust event. Tectonics, 22(4), 1034-1047. https://doi.org/10.1029/2002TC001422, 2003.

Roger, J.: Records of the 5 March 2021 Raoul Island transoceanic tsunami around the Pacific Ocean. New Zealand Journal of Geology and Geophysics, 1-16, https://doi.org/10.1080/00288306.2023.2225859, 2023.

Roger, J., Bull, S., Watson, S., Mueller, C., Hillman, J., Wolter, A., Lamarche, G., Power, W., Lane, E., Woelz, S., and Davidson, S. A review of approaches for submarine landslide tsunami hazard identification and assessment. In: Switzer, A., et al. (Eds): Special issue on Submarine Geohazards in/along the western Pacific Ocean, Marine and Petroleum Geology, 162, 106729, https://doi.org/10.1016/j.marpetgeo.2024.106729, 2024.

Roger, J., Pelletier, B., and Aucan, J.: Update of the tsunami catalogue of New Caledonia using a decision table based on seismic data and marigraphic records, Nat. Hazards Earth Syst. Sci., 19, 1471–1483, https://doi.org/10.5194/nhess-19-1471-2019, 2019.

Roger, J., Pelletier, B., Duphil, M., Lefèvre, J., Aucan, J., Lebellegard, P., Thomas, B., Bachelier, C., and Varillon, D.: The Mw 7.5 Tadine (Maré, Loyalty Islands) earthquake and related tsunami of 5 December 2018: seismotectonic context and numerical modeling, Nat. Hazards Earth Syst. Sci., 21, 3489–3508, https://doi.org/10.5194/nhess-21-3489-2021, 2021.

Roger J., Pelletier B., Gusman A., Power W., Wang X, Burbidge D., and Duphil M.: Potential tsunami hazard of the southern Vanuatu subduction zone: tectonics, case study of the Matthew Island tsunami of 10 February 2021 and implication in regional hazard assessment. Nat. Hazards Earth Syst. Sci., 23, 393–414, https://doi.org/10.5194/nhess-23-393-2023, 2023a.

Roger J., Ashraf, S., Pelletier, B., Krippner, J., Bani, P., Gusman, A.R., Thomas, B., and Kali, J.-C.: The East-Epi Volcano submarine eruption and associated tsunami of 31 January 2023: a powerful event in the shadow of the HTHH eruption. American Geophysical Union, Fall Meeting 2023, 2023b.

Romano, F., Molinari, I., Lorito, S., and Piatanesi, A.: Source of the 6 February 2013 M w= 8.0 Santa Cruz Islands Tsunami. Natural Hazards and Earth System Science, 15(6), 1371-1379, https://doi.org/10.5194/nhess-15-1371-2015, 2015.

Sahal, A., Pelletier, B., Chatelier, J., Lavigne, F., and Schindelé, F.: A catalog of tsunamis in New Caledonia from 28 March 1875 to 30 September 2009, Comptes Rendus Geoscience, 342, 434– 447, https://doi.org/10.1016/j.crte.2010.01.013, 2010.

Shanmugam, G.: Process-sedimentological challenges in distinguishing paleo-tsunami deposits. Nat Hazards 63, 5–30, https://doi.org/10.1007/s11069-011-9766-z, 2012.

Shorten, G.G.: Summary of earthquake and tsunami damage assessment in Port Vila, January 2002 supplement, ITIC Newsletter, vol XXXIV, n° 1, 5 p., 2002.

Soloviev, S. L., and Go, C. N.: A catalogue of tsunamis on the western shore of the Pacific Ocean (173–1968) (Canadian Translation of Fisheries and Aquatic Sciences, 5077, 1984), Nauka Publishing House, Moscow, USSR, 310 pp., 1974.

Spiske, M., Tang, H., & Bahlburg, H.: Post-depositional alteration of onshore tsunami deposits–Implications for the reconstruction of past events. Earth-Science Reviews, 202, 103068, https://doi.org/10.1016/j.earscirev.2019.103068, 2020.

Skoglund, P., Posth, C., Sirak, K. et al.: Genomic insights into the peopling of the Southwest Pacific. Nature 538, 510–513. https://doi.org/10.1038/nature19844, 2016.

Sydney Morning Herald: Volcanic eruption at the New Hebrides. A tidal wave. https://trove.nla.gov.au/newspaper/article/14407505, 1901.

Synolakis, C.E., Bardet, J.P., Borrero, J.C., Davies, H.L., Okal, E.A., Silver, E.A., Sweet, S., and Tappin, D.R.: The slump origin of the 1998 Papua New Guinea tsunami. Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, 458(2020), 763-789, https://doi.org/10.1098/rspa.2001.0915, 2002.

Taylor, F. W.: Quaternary vertical tectonics of the central New Hebrides island arc. Proc. Ocean Drill. Program Initial Rep., 134, 33 – 42, 1992.

Taylor, F.W., Isacks B.L., Jouannic C., Bloom A.L., and Dubois J.: Coseismic and Quaternary vertical tectonic movements, Santo and Malekula islands, New Hebrides island arc. J. Geophys. Res., 85(B10), 5367-5381, 1980.

Tendrayen, M.: Modélisation numérique du tsunami du 2 janvier 2002 au Vanuatu. Rapport de stage d'ingénieur ENSIM. 63 p., 2006.

TL/ICMMG: TL/ICMMG Global Historical Tsunami Database. Institute of Computational Mathematics and Mathematical Geophysics SB RAS, Tsunami Laboratory, Novosibirsk, Russia. http://tsun.sscc.ru/gtdb/default.aspx [Last accessed on 06/09/2023], 2023.

Tryon, D.T. and Hackman, B.D.: Solomon Islands languages: An internal classification. Dept. of Linguistics, Research School of Pacific Studies, The Australian National University. https://openresearch-repository.anu.edu.au/bitstream/1885/145227/1/PL-C72.pdf, 1983.

Wallez, S.: Etude des impacts socio-économiques des menaces volcaniques et autres risques naturels sur l'archipel du Vanuatu (Mélanésie). Mémoire DESS Sciences de l'environnement, Université Louis Pasteur de Strasbourg – Ecole et Observatoire des Sciences de la Terre, 177 p., 1998.

Walter, R., & Sheppard, P.: A review of Solomon Island archaeology. Lapita, ancestors and descendants. New Zealand Archaeological Association, Auckland, New Zealand, 35-72, 2009.

Witter, J.B. and Self, S.: The Kuwae (Vanuatu) eruption of AD 1452: potential magnitude and volatile release. Bull Volcanol (2007) 69: 301–318, https://doi.org/10.1007/s00445-006-0075-4, 2007.

Woodward, K.: A political memoir of the Anglo-French condominium of the New Hebrides (p. 93). ANU Press. https://library.oapen.org/handle/20.500.12657/33262, 2014.

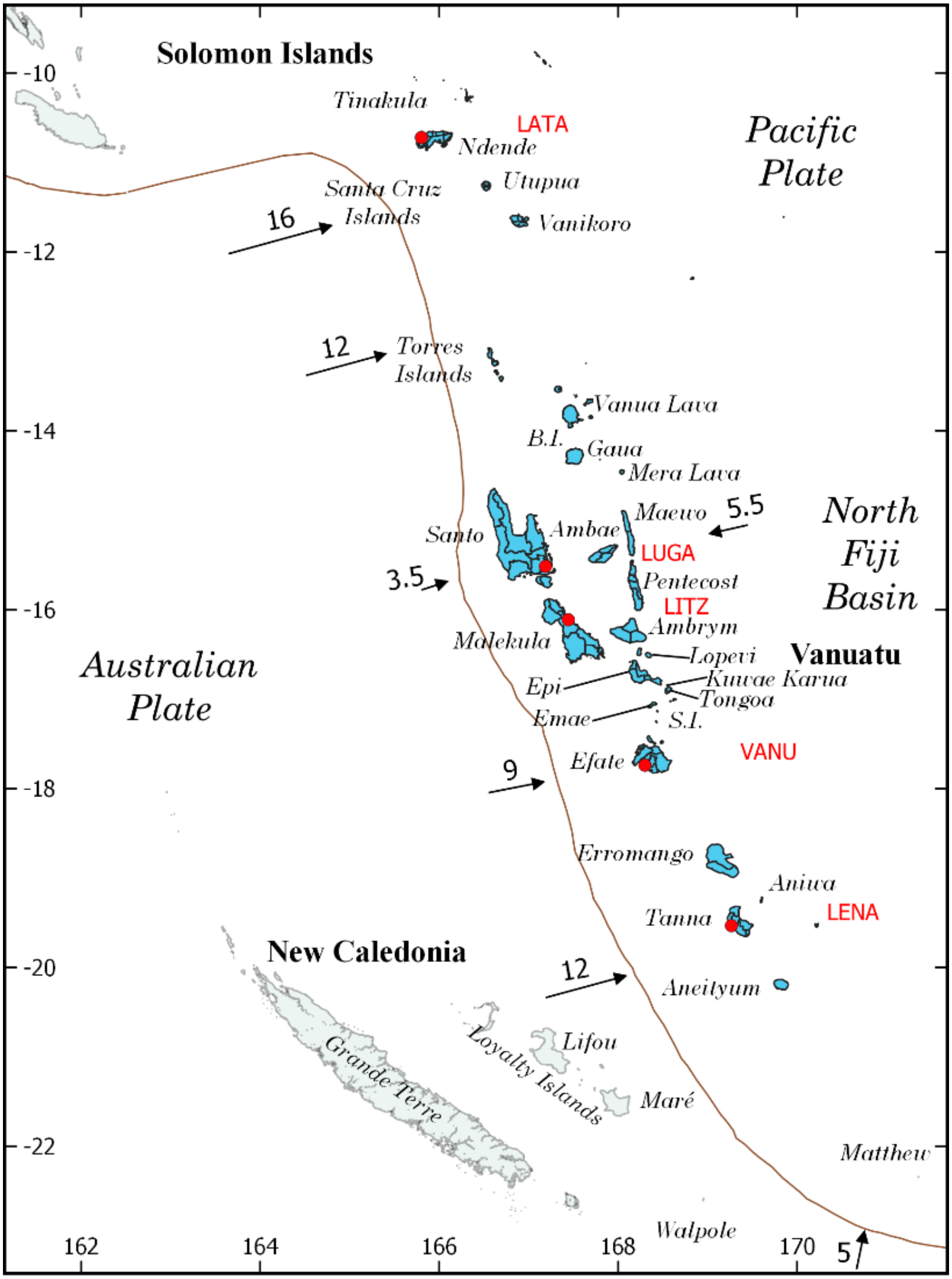

Figure 1 The Vanuatu Arc at the boundary between the Australian and the Pacific tectonic plates. The convergence rates are symbolized with the black arrows (values from Calmant et al., 2003, are indicated in cm/year). The five coastal tide gauges are symbolized with red circles.

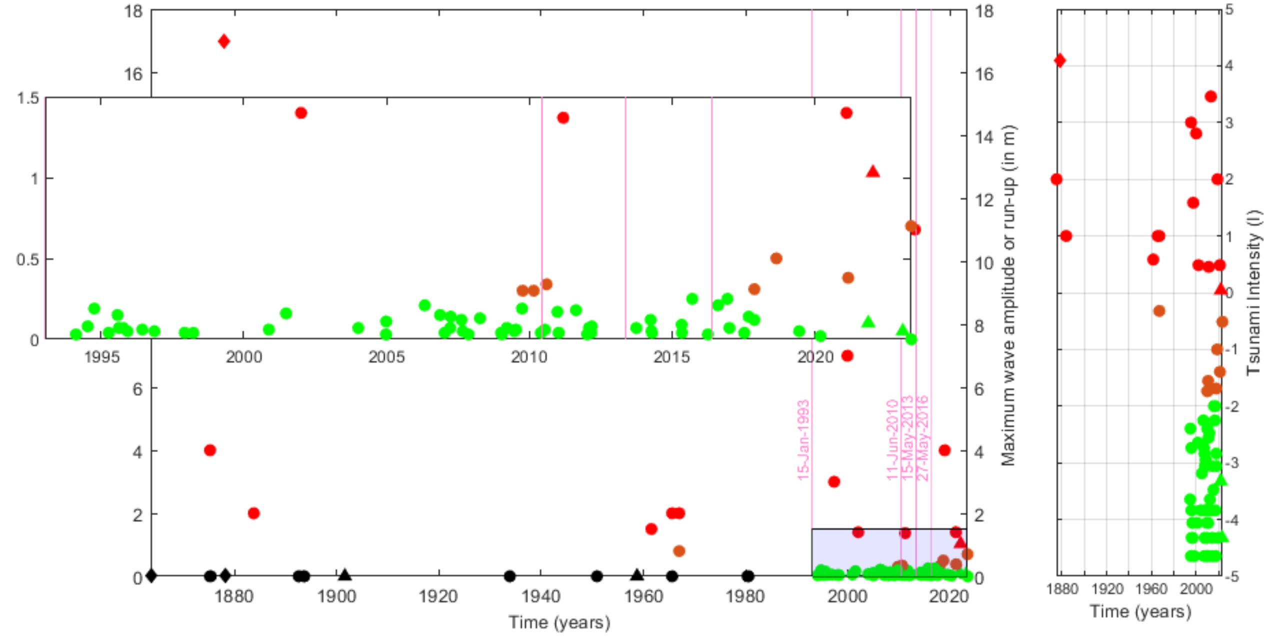

Figure 2 Tsunami maximum recorded amplitude or maximum elevation run-up for each event reported in Vanuatu Arc and listed in Table S1 (left plot). Circles represent tsunamis triggered by earthquakes, triangles represent those triggered by volcanic eruptions, and diamonds represent tsunamis which could have either an earthquake or volcanic origin. The threat level code is provided with green (0-0.3 m), orange (0.3-1 m) and red (1 m and above) colours. The black colour represents the tsunamis reported in Vanuatu Arc without any amplitude or run-up values provided. The vertical pink lines symbolize the beginning of the period of data availability for the five tide gauges located in the Vanuatu Arc. The light blue rectangle (bottom right of the figure) symbolizes the part of the plot zoomed in. The right plot presents the tsunami intensity based on Iida (1963) scale.

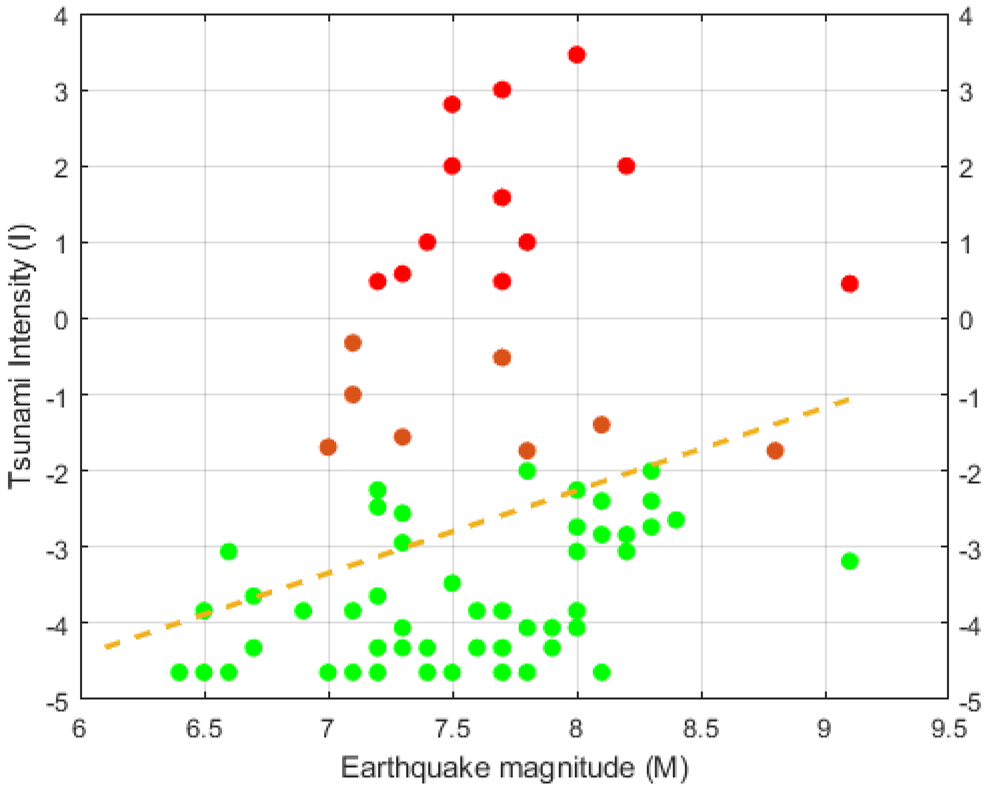

Figure 3 Dependence of the tsunami intensity as obtained using Iida and Imamura formulae on the earthquake magnitude. Linear regression is represented with the orange dashed line. The dots colour code is related to the maximum wave amplitude or vertical run-up and refers to the threat level ranges: 0-0.3 m: green symbols ; 0.3-1.0 m : orange symbols ; above 1.0 m : red symbols.

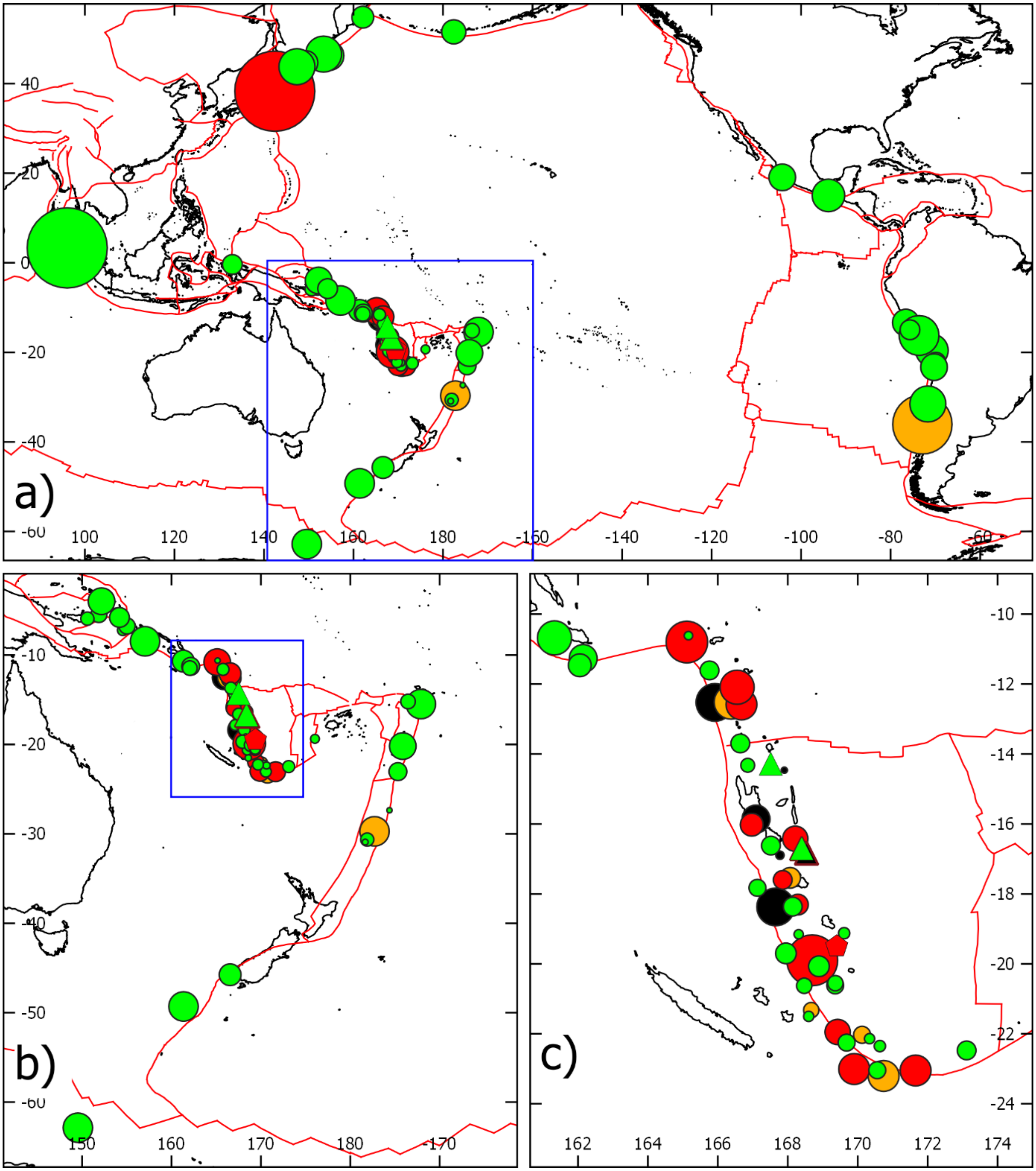

Figure 4 Location of the sources of tsunami reported/recorded in Vanuatu Arc. (a) Oceanic scale ; (b) Southwest Pacific Ocean scale ; (c) Vanuatu Arc scale. The red lines symbolize the plate boundaries; the blue rectangle in (a) represents the extent of (b) and in (b) the extent of (c); earthquake sources are represented with circles (size is function of the magnitude), volcanic eruptions with triangles and both earthquake and volcanic source by a pentagon; Maximum wave amplitude or vertical run-up refers to the threat level ranges: 0-0.3 m: green symbols ; 0.3-1.0 m : orange symbols ; above 1.0 m : red symbols ; no amplitude or run-up information : black symbols.

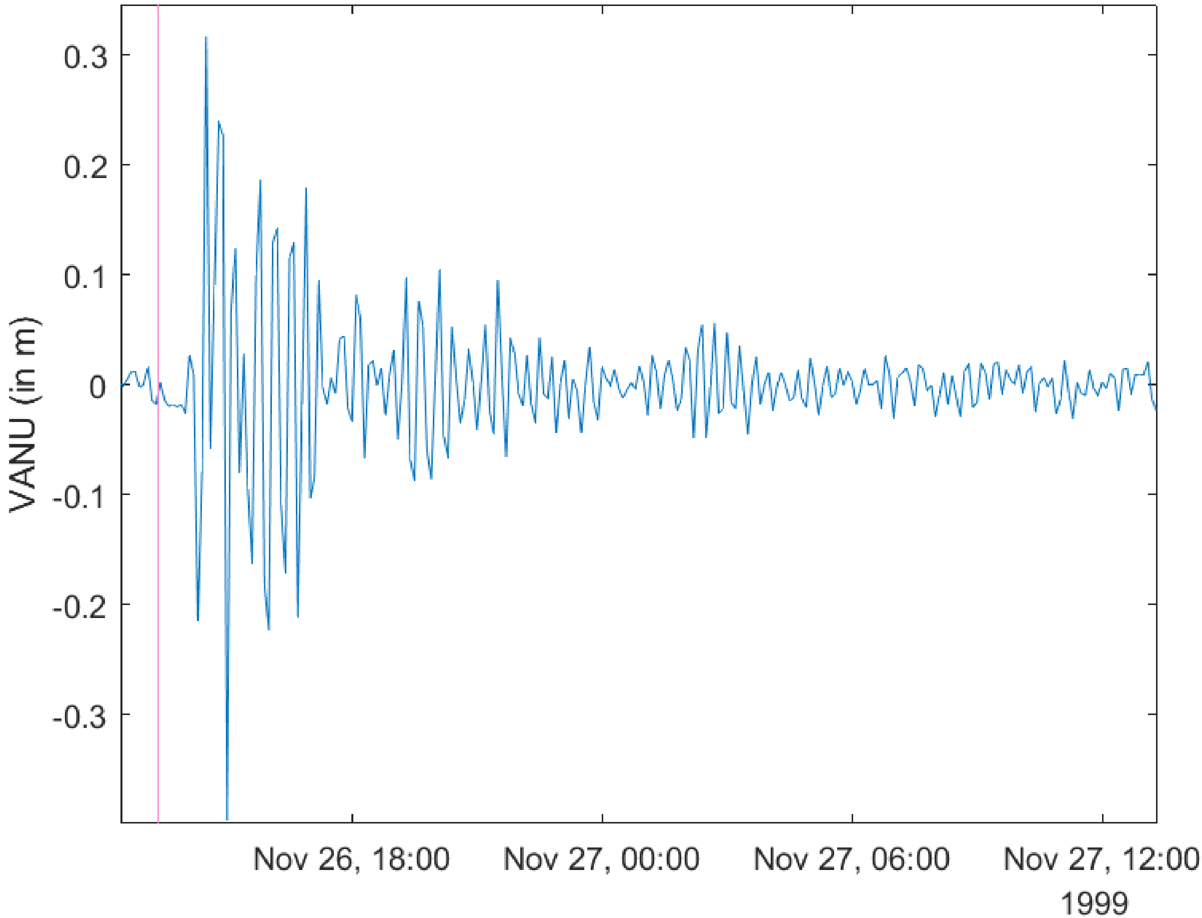

Figure 5 Records on Port Vila coastal gauge of the 26 November 1999 tsunami triggered by a Mw 7.5 earthquake east of Ambrym Island (6 min sampling rate data). The vertical red line symbolizes the earthquake time.

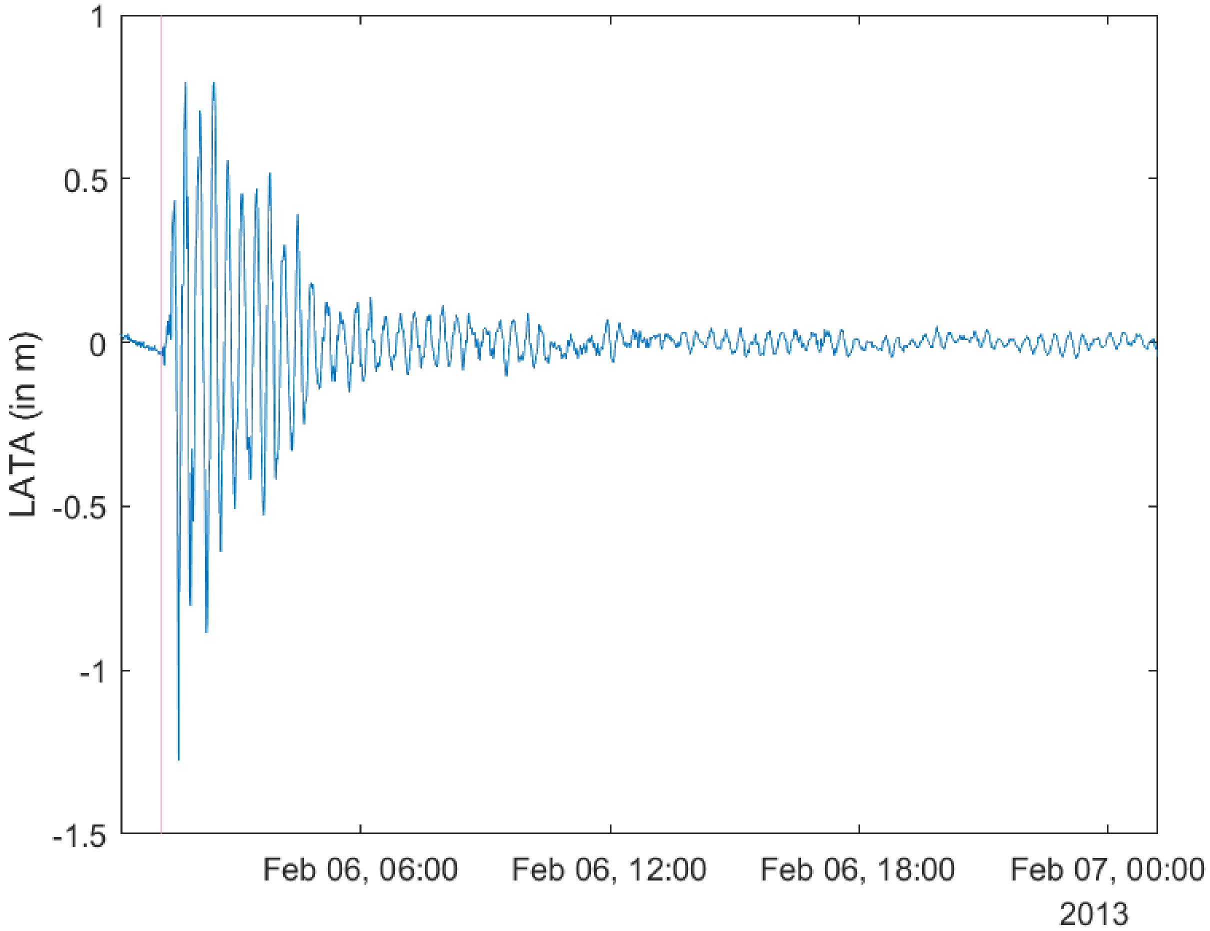

Figure 6 Records on Lata Wharf coastal gauge of the 6 February 2013 tsunami triggered by a Mw 8.0 earthquake west of Ndende Island in the Santa Cruz Islands group (1 min sampling rate data). The vertical red line symbolizes the earthquake time.

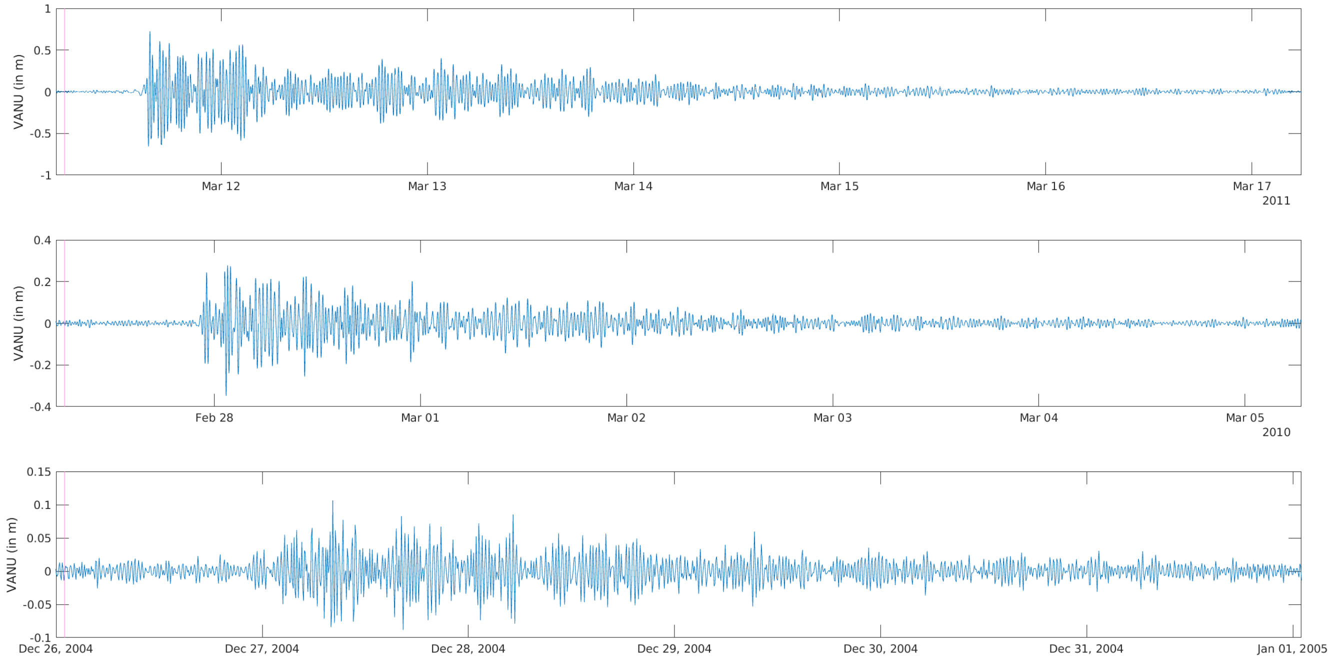

Figure 7 Records on Port Vila coastal gauge of 3 transoceanic tsunamis during 6 days after each related earthquake: (bottom) the 26 December 2004 tsunami triggered by the Mw 9.1 Sumatra earthquake in Indonesia; (middle) the 27 February 2010 tsunami triggered by the Mw 8.8 Maule earthquake in Chile; (top) the 11 March 2011 tsunami triggered by the Mw 9.1 Tōhoku earthquake in Japan; the vertical red line symbolizes the earthquake time. The data was detided using a bandpass filter. (Top and middle: 1 min sampling rate data; bottom: 6 min sampling rate data).

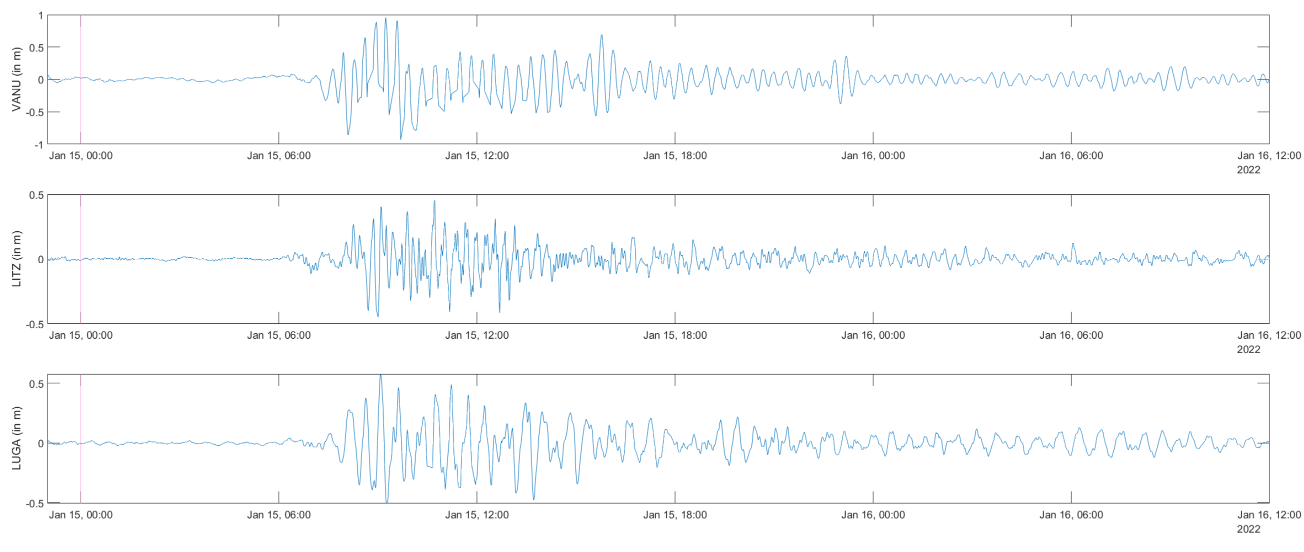

Figure 8 Records of the HTHH tsunami on three of the five coastal gauges of the Vanuatu Arc. From South (top) to North (bottom): VANU, LITZ & LUGA. The red vertical line indicates the time of the main volcanic eruption.

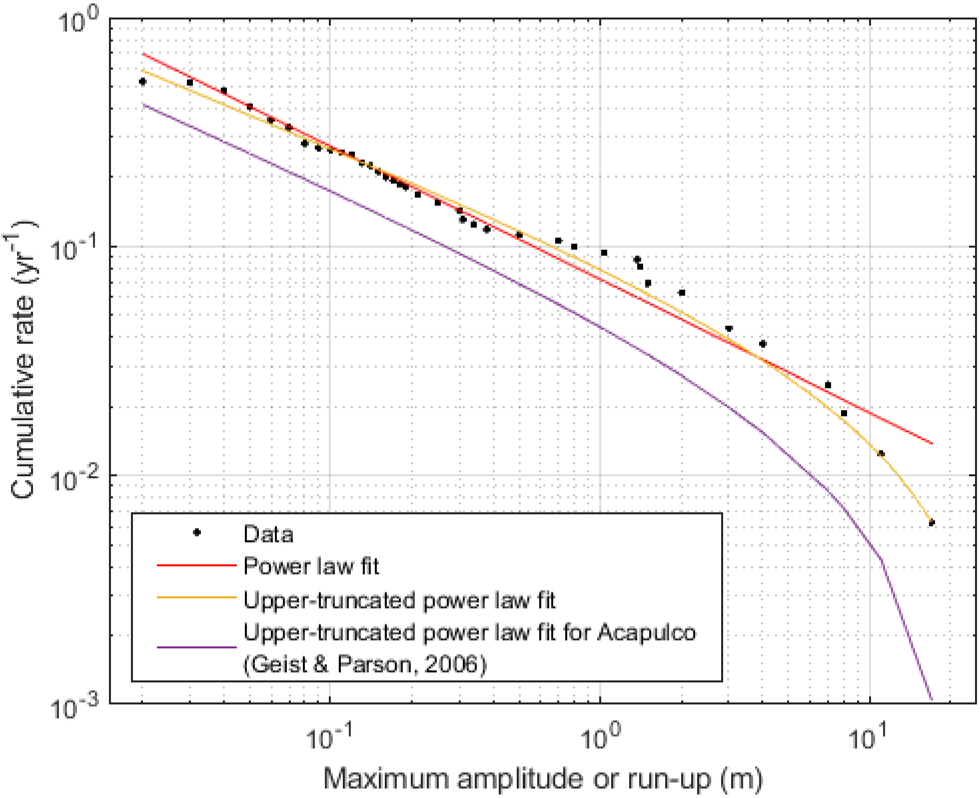

Figure 9 Tsunami exceedance frequency curve showing the cumulative rate of tsunamis (yr-1) exceeding the maximum amplitude or run-up value given by the abscissa for the present tsunami catalogue of the Vanuatu Arc over the period 1863-2023. The black dots represents the data; the red line represents the trend with a power law fit (a=0.0716; b=-0.581); the yellow line represents the trend using an upper-truncated power law fit based on the work from Burroughs and Tebbens (2001) with C=0.0993 and D=-0.4626; the purple line is an example of the trend using an upper-truncated power law fit for tsunami exceedance frequency for Acapulco (Geist and Parsons, 2006).

Table 1 Coastal sea-level gauges in Vanuatu Arc: location, start date of data availability, type of sensor and link toward the dataset (data from VLIZ/IOC, 2023 and BOM: http://www.bom.gov.au/oceanography/projects/spslcmp/data/index.shtml).

Coastal gauge	Location	Lon	Lat	Data available since	Type of sensor	sampling rate (in min)	Coverage	more information
Lenakel	Tanna	169.265953	-19.53256	27/05/2016	Radar	1		http://www.ioc-sealevelmonitoring.org/station.php?code=lena
Port Vila	Efate	168.307694	-17.755333	15/01/1993	Aquatrak	1		http://www.ioc-sealevelmonitoring.org/station.php?code=vanu +BOM http://www.bom.gov.au/oceanography/projects/spslcmp/data/index.shtml : 15 January 1993 – actual (gap between 29 March 1993 and 26 January 1994 / Data from 1976 to 1983 are inaccessible (see text)
Litzlitz	Malekula	167.44397	-16.11283	27/05/2016	Radar	1		http://www.ioc-sealevelmonitoring.org/station.php?code=litz
Luganville	Santo	167.1886	-15.5156	15/05/2013	Pressure	1		http://www.ioc-sealevelmonitoring.org/station.php?code=luga
Lata	Ndende	165.8019	-10.7208	11/06/2010	Radar	1		https://www.ioc-sealevelmonitoring.org/station.php?code=lata

Supplementary material

Table S1 Catalogue of the tsunamis having been reported and/or recorded in the Vanuatu Arc since 1863. The colour of the lines depends on the maximum wave amplitude or vertical run-up value, referring to the threat level ranges: 0-0.3 m: green; 0.3-1.0 m: orange; above 1.0 m: red; no amplitude or run-up information: black. No values are indicated by “NaN”.