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## Coastline shift seaward by lahar deposits, leading to the formation of new beaches, Ambae volcano --Manuscript Draft--

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# Coastline shift seaward by lahar deposits, leading to the formation of new beaches, Ambae volcano

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## Abstract

Lahar deposits resulting from the eruption of Ambae (Vanuatu) in 2017-2018 were transformed into black sand beaches at the outlets of the flowpaths. This occurrence represents a novel and unreported phenomenon for Ambae. This study proposes that the combination of steep slopes with relatively short flowpaths (5-10 km) and substantial ash accumulation at the summit facilitated the rapid transfer of material from the volcanic summit to the coastal zone, providing the energy necessary for the gradual seaward extension of the coastline and the formation of beaches. The occurrence of this phenomenon is limited to specific areas, contingent upon the distribution of ash deposits on the summit. The western section of the crater's summit has predominantly accumulated ash, partially due to the consistent presence of trade winds. This region coincides with the origins of the flowpaths supplying the lahar zone. Since 2018, the newly formed beaches persist, offering promising prospects for the island's development, including the identification of freshwater sources. Furthermore, our results suggest that a combination of the lahar and landslide event triggered the destruction of the village of Waluembue. Paradoxically, the lahar's arrival preceded the landslide, providing a wake-up call to the inhabitants and giving them crucial time to evacuate before the catastrophic impact.

Keywords: Ambae volcano, 2017-2018 eruption, ash deposit, lahar, coastline change

## Introduction

A lahar, or volcanic mudflow, is a dynamic and turbid debris flow or a hyperconcentrated flood that occurs on volcanic slopes regardless of temperature, and consists primarily of ejected fine ash or pyroclastic materials (Zobin, 2012). Initially, a lahar typically manifests itself as a debris flow for the first few kilometers, but then transforms into a hyperconcentrated flood flow (Takahashi, 2007). Lahars can be syn-eruptive or post-eruptive and can even occur independently of eruptive events, particularly following landslides (Vallance, 2005). Precipitation can trigger post-eruptive or secondary lahars, while an eruption can lead to melting of snow or glacial ice and rapid overflow of water bodies that can generate lahars (Thouret et al., 2020). Lahars can reach speeds of tens of kilometers per hour and their high density poses a significant threat, capable of destroying infrastructure and homes and engulfing entire towns. The 1985 Nevando del Ruiz eruption serves as a prominent example of a devastating lahar event (Sigurdsson and Carey, 1986). However, as lahars move away from the steep slopes near the volcano's summit towards lower elevations, they gradually slow down, depositing their sediment loads and decreasing in size and strength. Depending on the volcano's morphology and the triggering mechanisms, lahars can travel to more than 20 km from a volcanic summit (Pierson et al. 2014), leaving lahar deposits along the flowpaths. In some cases, lahars have reached the coastline and triggered tsunamis (Poisson and Pedreros, 2010), while in other cases, they enhance shoreline advance or simply reinforce shallow sediments (Kuenzi et al., 1979; Encinas et al., 2006; Major et al., 2016; Duller et al., 2014). Here we present a case where lahar deposits have profoundly transformed the coastline following the major 2017-2018 eruptive event at Ambae.

## Ambae volcano and its major eruption of 2017-2018

Ambae (or Aoba) is a basaltic shield volcano located in the central part of the Vanuatu archipelago (**Fig. 1**) rising ~3800 m from the sea floor with a volume of 2500 km<sup>3</sup> (Warden, 1970). The aerial extent of the volcano is ~405 km<sup>2</sup>, aligned along a north-east to south-west axis. The central portion of the volcano is dominated by a broad pyroclastic cone, with a summit elevation of 1496 m above sea level. This cone contains three lakes within a prominent 2000 year old nested caldera (Warden, 1970). In 2005, these lakes held a total of 57x10<sup>6</sup> m<sup>3</sup> of water, 70% of which was in the acidic crater lake Vui (Bani et al., 2009a). Notably, this crater lake serves as the focal point of the 2017-2018 eruptive activity, which marked the third eruption of the volcano after a dormancy of ~300 years. The previous dormancy periods ended in the early 1990s (Wiert, 1995; Nemeth et al., 2006; Bani et al., 2009b). There is disagreement about the magnitude of this most recent eruption. Some researchers propose a Plinian eruptive event (Moussallam et al., 2019), while others suggest a lower intensity (Malinina et al., 2021). Nevertheless, there is a consensus that it was a significant event that unfolded from 5 September 2017 to 5 August 2018. The eruption triggered two states of emergency and twice forced the evacuation of Ambae's 11,000 inhabitants, in October 2017 and July 2018. Lava fountains, lava flows and strombolian activity were observed at the summit, the first such events since the NduiNdui flow in 1670 (Williams et al., 1964). Acid rain and ash fallout destroyed over two-thirds of the island's vegetation. Within the caldera, the dense vegetation before the eruption was transformed into a desolate landscape, devoid of vegetation and covered in thick layers of ash deposits. This ash cover extended over the central part of the island. Between March and July 2018, ash emissions reached levels that completely obscured daylight, forcing residents to use electric flashlights.

## Methodology

To assess the extent of lahar deposits on Ambae, a series of field surveys were conducted along the island's coastline, in 2017, 2018, 2021, 2022 and 2023. During these surveys, empirical data on the deposits were gathered and photographs captured during the field observations were analysed to understand the formation and evolution of the deposits. In addition, complementary analyses were carried out by retrieving and examining relevant images from various sources, including websites and social networks. Similar to previous studies (e.g., Kunrat et al., 2020), a thorough screening of satellite images available on Google Earth was conducted to determine the spatial distribution of the lahar deposits. In an attempt to analyse these deposits quantitatively, the data were geolocated, integrated into a database and processed using the QGIS program. Systematic mapping was carried out to document shoreline changes and catalogue areas covered by lahar deposits. The potential lahar flowpaths proposed by (Bani et al., 2009a) were incorporated to facilitate discussions on the formation of new coastlines as a result of lahars. Efforts were also made to assess the distribution of ash deposits using images taken by satellite sensors and shared on social networks (e.g., <https://twitter.com/i/status/983918236931579906>; <https://pbs.twimg.com/media/Da72oNaU0AAL6ii?format=jpg&name=900x900>, etc.).

## Results and discussion

### Genesis of lahars

The possibility of lahars on Ambae has often been highlighted in volcanic risk awareness programs but there was no recent eyewitness accounts of lahar events. Few information is available about a destructive and deadly lahar in 1870, which reportedly destroyed villages on the south-eastern flank of the volcano and caused >100 deaths, and another

in 1914, both supposedly triggered by summit eruptions (Siebert et al., 2010). Previous studies have suggested a period of dormancy from the Nduindui lava flow in 1670 (Warden, 1970) until the early 1990s (Wiert, 1995; Bani et al., 2019b). More recently, Cronin et al. (2004) identified volcanic hazard risk zones and potential lahar flowpaths by integrating scientific and traditional knowledge, while Bani et al. (2009a) provided additional insights into potential lahar sources based on crater lake volumes and summit morphology. In the latter paper, the authors suggested that the lowest point of the caldera rim is on the eastern part of Manaro Lakua and that the two streams that originate near this lowest point are likely to direct lahars towards the south-east coast of Ambae. However, although this region experienced the island's deadliest lahar in 1870, according to Siebert et al. (2010), it was not significantly affected by eruption-induced lahars of 2017-2018. This raises the possibility that the 1870 and 2017-2018 lahars were induced by different phenomena. Indeed, Bani et al. (2009a) proposed that the initiation of the 1870 event might have been due to the overflow from Lake Manaro Lakua, potentially unrelated to a volcanic eruption. In contrast, previous studies have strongly emphasised the possibility of a significant phreatic eruption, with a substantial volume of water being transferred to the flanks. This concern was supported by examples from other volcanoes, such as Kelud (Indonesia) in 1919, where an eruption released  $4 \times 10^7 \text{ m}^3$  of water from a Kelud's lake, resulting in lahars that travelled nearly 40 km downstream, covering over  $130 \text{ km}^2$ , and causing more than 5000 deaths (Vallance and Iverson 2015). However, during the 2017-2018 Ambae eruption, there was no discharge of water from Lake Vui. Therefore, despite the high intensity of eruptive activity, the  $\sim 57 \times 10^6 \text{ m}^3$  of water did not trigger lahars. Instead, the water volume progressively diminished by evaporation, facilitated by the high thermal energy of the eruption. This process reduced the risk of water being expelled from Lake Vui. Hence, the numerous lahars observed during and after the 2017-2018 eruption were induced by the remobilisation of the ash deposits triggered by rainfall (**Fig. 2**).

The first occurrence of lahar events was reported in January 2018, coinciding with heavy rainfall induced by tropical depression Fehi (from January 26 to January 30, 2018) (**Fig.3**). Subsequent episodes of heavy rainfall coincided with tropical cyclone Gita (8 February to 18 February 2018), tropical cyclone Hola (3 March to 11 March 2018), tropical depression Linda (10 March to 15 March 2018) and tropical depression Iris (22 March to 7 April 2018). The majority of lahar events occurred between January and April 2018, coinciding with these cyclones and tropical depressions. Figure 4 shows images of the lahar deposits observed during the field of survey conducted in May 2018 following the cyclonic events. Significant changes were observed, particularly along the coastline where lahars reached the sea. Substantial lahar deposits were observed at the outlet of the flowpaths at Loone Ngwaravu (south of Ambae), new beaches were formed along the southern and northern coastlines, and springs previously submerged below sea level emerged at the surface. In the northern part of Ambae, the village of Waluembue was completely destroyed by a lahar-triggered event on 31 March 2018. The combination of extensive ash deposits and cyclonic rainfall were the main factors contributing to the numerous lahars observed in Ambae between January and April 2018. Lahar events continued after April 2018, but were of a relatively smaller magnitude.

### **Coastline retreat induced by lahar deposits**

The 2018 lahar deposits on Ambae have resulted in significant changes to the coastline, leading to the formation of extensive beaches in various area along the northern and southern coastlines. Historically known as the “Black Stone Island” due to the ancient lava flows that shaped the coastline, the 2018 lahar deposits have profoundly reshaped the

landscape of Ambae. Significant beach extension has occurred in several areas along the northern coast, particularly at sites such as Loone Kwekwehu and Loone Lakua, where the shoreline has moved seaward by a maximum of approximately 40 m and 90 m respectively (**Fig. 5**). Similarly, along the southern coast, at Lolobanga, Loone Ngwaravu and Redcliff, the coastline has moved seaward by up to 20 m, 30 m and 40 m respectively (**Fig. 5**). It is important to note that the data and figures for the northern coast, were derived from the April, 2018 satellite image, while the eruptive activity was still ongoing with subsequent ash deposition. It is therefore possible that the extent of coastline expansion has been further accentuated since then. In addition, only the Loone Lakua lahar area was visited in 2023, hence the updated representation of the new coastline for this beach (**Fig. 5**).

In order to develop such beaches, not only did the large volume of material need to be remobilised and transported by lahars, but the kinetic energy had to be high enough to bring this material to the coast. The specific volume of ash produced by the 2017-2018 eruption is not quantified in this work, however, the duration of the eruption, the intensity of the event and the large extent of the ash fall indicate that the volume of material available for lahars is significant. This was confirmed by field observations. It should also be noted that lahars removed some of the transported volume along their path.

The lahar flowpaths identified in previous studies (Bani et al., 2009a; Cronin et al., 2004) have relatively short distances (5-10 km), deep gullies and very steep slopes with an average gradient of 20-25% (maximum of 40%) on the northern and southern flanks (Bani et al., 2009a). As a result, heavy rainfall quickly leads to lahars that subsequently reach the coast with significant volumes of volcanic products and sufficient energy to progressively shift the coastline towards the open sea, resulting in the formation of new beaches.

A fascinating aspect of this coastline transformation is the emergence of previously unknown freshwater sources (Fig 6). These sources were originally 2-3 metres below sea level. In the north-west of Ambae, particularly at Loone Lakua, as the coastline extended towards the sea, the inhabitants discovered a spring with a constant flow of fresh water. This discovery proved invaluable to the residents of the Loone evacuation centre during the crisis. A similar spring of the same type was also discovered on the southern side of Ambae Island.

### **Ash deposits influencing the distribution of lahar deposits**

Previous studies (Bani et al., 2009a; Cronin et al., 2004) have highlighted the potential for lahars on Ambae Island and identified the main flow paths and lahar-prone areas. Their results indicated that the northern and southern regions of the island are particularly susceptible to lahars, which is consistent with the lahar deposits observed in this study. However, these studies did not investigate the potential for lahar deposits along the coastline and the subsequent formation of new beaches. Traditionally, Ambae has been characterised by rocky coastlines with limited boat moorings. However, the landscape has been significantly transformed by lahar deposits. The first appearance of lahar deposits along the coast was observed in January 2018, and the phenomenon continued throughout 2018 and beyond, resulting in the formation of extensive black beaches. Initially, there were concerns about the ability of these sandy areas to withstand continuous wave action. However, four (4) years later, these beaches have not only endured, but have also continued to grow in size due to the large quantity of ash that remained at the summit of the volcano. As a result, the local population has begun to consider potential tourism development opportunities arising from these changes.

The distribution of lahar deposits is not uniform along the entire coastline of Ambae. Instead, they appear to be more concentrated in certain sectors of the island, particularly in the areas of Loone Lakua, Waluembue and Lombaha in the north coast and from Loone Ngwaravu to Redcliff on the south coast. At least nineteen (19) different lahar deposits of varying sizes were identified and mapped (**Fig.7**). The coastal extent affected by lahar deposits is 2.4 km at Loone, 2.8 km at Waluembue and 0.3 km along Lombaha. In the south, about 7.8 km of coastline is affected by lahar deposits. In

total, about 10 km of Ambae's coastline is affected by lahar deposits, which is about 10% of the island's total coastline. We estimate that a total of 0.31 km<sup>2</sup> of new coastal land was created by the lahar deposits (Table 1), with almost equal contributions from the northern (48%) and southern (52%) regions. In the north, Loone Lakua and Waluembue were the major contributors, while in the south, Loone Ngwaravu had the largest area of lahar deposits. It should be noted that the estimated surface area does not include lahar deposits along the flow paths. In addition, only the largest deposits visible on satellite imagery and confirmed on the ground were mapped, potentially resulting in exclusion of smaller deposits, some of which may have been washed out by sea waves. The surface estimates provided should therefore be regarded as minimum values.

**Table 1.** Estimated Areas of Lahar deposits

<b>North Ambae</b>	<b>Area (km<sup>2</sup>)</b>	<b>Lahar extent along the coast (km)</b>
Loone Lakua and Loone Kwekwehu	0.06	2.2
Waluembue	0.08	2.4
Lombaha	0.008	0.3
<i>Sub-Total</i>	<i>0.15</i>	<i>4.9</i>
<b>South Ambae</b>		
Lolobanga	0.003	0.2
Combined Loone Ngwaravu-Loone gwaravu east-Red cliff	0.16	5.2
<i>Sub-Total</i>	<i>0.16</i>	<i>5.4</i>
<b>Total</b>	<b>0.31 km<sup>2</sup></b>	<b>10.3 km</b>

Although precise mapping of ash deposits has not been carried out, it is clear that the eruptive phases were accompanied by significant ash fall events. Nevertheless, this paper has attempted to approximate the distribution of ash deposits using Google Earth imagery. December 2017 imagery clearly showed ash extending from the summit crater lake and covering the western areas (Figure 7). The January 2018 image showed ash covering the entire summit region. By May 2018, ash deposits were observed to have extended further towards the north-eastern and south-western regions. In July 2018, successive ash releases were recorded by Hinemari and Terra Modis, culminating in a substantial ash discharge that blanketed the whole island on 27 July, 2018. Superimposing these ash distributions, it is clear that the western part of the summit received the highest concentration of ash. This area coincides with the origin of the flowpaths leading north to the Loone Lakua area and south to the area between Loone Ngwaravu and Redcliff. Furthermore, the eruption lasted for a year, and regular ash emissions were observed by residents in the western part of Ambae, consistent with the prevailing south-easterly winds. Consequently, it is reasonable to expect a greater amount of ash deposition on the western part of the summit compared to the eastern part. This discrepancy may explain the lower occurrence of lahars and the absence of new beaches on the southeastern part of Ambae. These observations suggest that the distribution of ash, which is predominantly concentrated on the western part of the summit, has influenced the distribution of lahar deposits and the subsequent formation of new beaches along the coast.

## Waluembue Case - a lahar paradox

In the early hours of 31 March 2018, at around 1:00am, residents of the village of Waluembue were suddenly awakened by a deafening sound reminiscent of a military aircraft passing overhead. This was how the locals described the sound, as Vanuatu residents are accustomed to the passage of aircraft such as the Casa or Hercules, especially during natural disasters. Soon after, they witnessed the first lahar in the western part of the village, which was strong enough to force people out of their beds. Some houses were flooded, forcing residents to move their belongings to the school building in the centre of the village. However, about half an hour later, an even louder noise reverberated through the village, forcing everyone to immediately flee to higher ground. Their timely evacuation came just moments before the second onslaught devastated the entire village. Fortunately, there were no casualties, but without the first, relatively modest lahar, the consequences would have been catastrophic. The only confirmed casualty resulting from lahars in Ambae following the 2017-2018 eruption was an individual in West Ambae who unwisely attempted to cross a stream on his quad bike when the muddy water was very high. **Figure 8** shows the before and after scenes of Waluembue village, demonstrating the complete destruction of the entire  $\sim 0.1 \text{ km}^2$  area of the village by the lahar.

The peculiarity of the Waluembue lahar is the significant remobilisation of large boulders, some up to a metre in diameter, towards the shoreline, ultimately contributing to a seaward shift of over 50 meters. This contrasts with the formation of new beaches in other areas, primarily composed of black sand. Notably, within the site, meter-sized boulders are mainly found in the upstream part of the village, closer to the mountain, while decimeter-sized boulders are prevalent on the beach. This arrangement of boulders is determined by a number of factors, including their size, weight, shape, gravity, speed and the terrain. As a result, on a given slope, smaller blocks tend to be transported to greater distances from the source, whereas larger and heavier boulders are often deposited closer to the origin. Thus the large boulders at the entrance to the village suggests that they came from an area close to the village. A significant scar on the hillside, less than 2 km north of the village, suggests that a landslide may have occurred during the event. Although this study has not directly investigated this particular site, its location along the flow path strongly suggests its involvement in the destruction of the village. Therefore, the most likely scenario for the Waluembue event involves a landslide triggered by lateral bank erosion by a lahar. The occurrence of the lahar prior to the destructive event supports this hypothesis, creating a paradoxical situation where the lahar also played a role in saving the lives of the villagers.

## Conclusion

In this paper, we have highlighted the changes that have occurred along the coast of Ambae island as a result of lahar deposits. In fact, large volumes of lahar deposits have been observed in different parts of the coast, at the mouths of the flow paths. Waves and currents have contributed and promoted the development of new beaches along the coastline, a phenomenon never reported on Ambae. The deep gullies, steep slopes (20-25%) and relatively short flow paths (5-10 km) constitute the main ingredients that allow rapid transfer of material from the top to the coast with kinetic energy (not calculated) sufficiently strong to promote progressive shoreline retreat over several tens of metres. However, apart from the case of Waluembue and Lombaha, most of the lahar deposits are located in Loone Lakua in the north and between Loone Ngwaravu and Redcliff in the south, contrasting with scenarios in previous works where two thirds of the island's surface is exposed to witnessed lahars. This work demonstrates that the observed lahar distribution was conditioned by the distribution of ash deposits, which were more important on the western part of the summit due to the regular presence of trade winds. It is on this western part of the summit that the flow paths that fed the lahar zones originated.



Despite the numerous lahars reported, there was only one confirmed fatality, but a catastrophic event completely destroyed the village of Waluembue. Our results show that it was a combination of lahar and landslide that cause this devastation, the former triggered the latter.

Five years after their formation, the beaches continue to remain with relatively little changes. This opens up new prospects for development. The lahar deposits have also allowed the inhabitants to discover new sources of water. The question is how long these new beaches will really last.

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## Declarations

Conflict of Interest - The authors declare there are no conflicts of interest

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## Figure captions

**Figure 1.** Ambae is the largest volcano in Vanuatu located in the northern part of the archipelago. It is a basaltic shield volcano that hosts three lakes on its summit, including Lake Vui, the center of the 2017-2018 eruptive activity. The red triangles correspond to active volcanoes.

**Figure 2.** Pictures of ash deposits at the summit of Ambae volcano. The entire vegetation was effected by the ash fall.

**Figure 3.** The trajectories of the tropical depressions and tropical cyclones between Jan. and Apr. 2018 that produced heavy rainfalls that triggered the lahars. Tracks are reproduced on the basis of cyclone tracking maps provided by [www.meteo.nc](http://www.meteo.nc). The color code indicates cyclone intensity: yellow corresponds to a category 1 cyclone, orange to a category 2 cyclone, red to a severe category 3 tropical cyclone, purple to a severe category 4 cyclone and black to a severe category 5 tropical cyclone. Blue corresponds to a tropical depression. The name of each cyclone is indicated at the beginning of each trajectory, and symbols are used to help distinguish them.

**Figure 4.** Lahar deposits and impacts observed in May 2018 after the cyclones. None of these phenomena have been observed in the past. A) Two photos of the same location on different dates, east of Loone (known as Lolotinge), NW Ambae. B) A new beach ~70m wide has formed at Saranamundu, northwest of Ambae. There was no beach in this area before the eruption. C) Lahar deposit over 3 m high observed on the Loone Ngwaravu flowpath, south of Ambae. Circles indicate cattle fence posts that were completely buried. D) Traces of the Waluebue event, the remains of the village church building; rocks and tree trunks that reached the shore. E) Freshwater discovered at Loone (NW Ambae) after coastline retreat. Satellite images show the extent of the new beach formed by the lahars.

**Figure 5.** Some of the main coastline changes following lahar events.

**Figure 6.** Emergence of water sources as a consequence of coastline retreat

**Figure 7.** Distribution of lahar deposits along the coast of Ambae. The vignettes give a little more detail on their distributions. The lahar flow paths (in blue) are modified from (Bani et al., 2009a) and the main paths taken by the lahars

since Jan. 2018 are thicker. Ash distributions as observed on available satellite images (Google earth) with their relative dates.

**Figure 8.** Two satellite pictures (from Google Earth) showing the situation at Waluembue village before and after the lahar event. A new flow path was enhanced by the lahar. Pictures show the blocks that reach the coast (A, B), the new flow path (D), the school building (C, F), the church house crushed by the large blocks (E, G) and a village house (H).

## Tables

Table 1. Estimated Areas of Lahar deposits

<b>North Ambae</b>	<b>Area (km<sup>2</sup>)</b>	<b>Lahar extent along the coast (km)</b>
Loone Lakua and Loone Kwekwehu	0.06	2.2
Waluembue	0.08	2.4
Lombaha	0.008	0.3
<i>Sub-Total</i>	<i>0.15</i>	<i>4.9</i>
<b>South Ambae</b>		
Lolobanga	0.003	0.2
Combined Loone Ngwaravu-Loone gwaravu east-Red cliff	0.16	5.2
<i>Sub-Total</i>	<i>0.16</i>	<i>5.4</i>
<b>Total</b>	<b>0.31 km<sup>2</sup></b>	<b>10.3 km</b>

## **Reviewer 1**

I have now had an opportunity to complete my review of your manuscript "Coastline extension offshore and emergence of new beaches triggered by lahar events on Ambae", submitted to the journal Bulletin of Volcanology. Overall, this is a short but interesting paper and my recommendation is for publication after minor revision. I have made annotations on a hard copy of the manuscript, mainly related to grammar and repetition, in addition to the following numbered points.

### **Resp.**

All corrections and comments are taken into account in the corrected version of the manuscript – thank you

a) The word "*permanently*" is removed from the sentence below in the corrected manuscript as we agree that we are only a few years away from the lahar deposits period.

*Here we present a case where lahar deposits have profoundly ~~and permanently~~ transformed the coastline following the major 2017-2018 eruptive event on Ambae.*

b) Wiart, **1995** is the correct year instead of **1945** as stated in the reference. Now corrected in the manuscript.

c) Citations of references in the manuscript are homogenized to the standard format, e.g. Cronin et al. (2004)

d) We remove the repetition as suggested – thank you

1. There are multiple papers that discuss shoreline advances due to volcanoclastic resedimentation in the aftermath of eruptions, including Kuenzi et al. 1979 (Geological Society of America Bulletin 90: 827-838), and Major et al. 2016 (Water Resources Research 52: 5075-5094), and others. The 1918 Katla jökulhlaups in Iceland extended the shoreline by up to 7 km in places for example.

### **Resp.**

Thank you for the references which are now included in the manuscript.

The following sentence has been removed from the manuscript: "*Nonetheless, there is currently no document evidence to our knowledge that extensively highlights widespread changes in coastal morphology associated with lahar deposits.*"

2. There are some contradictions in this paragraph that need clarification. Are you suggesting that the 1870 lahar was triggered by an unrecorded eruption through Lake Manaro Lakua, and hence had a different mechanism than the 2017-2018 rain-triggered events.

### **Resp.**

We thank you for the comment and understand that our paragraph was not clear. We have therefore modified it to better reflect the point we developed below :

*This raises the possibility that the 1870 and 2017-2018 lahars were induced by different phenomena. Indeed, Bani et al. (2009a) proposed that the initiation of the 1870 event might have been due to the overflow from Lake Manaro Lakua, potentially unrelated to a volcanic eruption. In contrast, previous studies strongly emphasized the possibility of a significant phreatic eruption with a substantial volume of water being transferred to the flanks. This concern was substantiated by instances on other volcanoes, such as Kelud Kelud (Indonesia) in 1919, where an eruption expelled  $4 \times 10^7$  m<sup>3</sup> of water from Kelut's lake, resulting in lahars that traveled nearly 40 km downstream, covered over 130 km<sup>2</sup>, and caused more than 5000 fatalities (Vallance and Iverson 2015). However, during the 2017-2018 eruption of Ambae, there was no expulsion of water from Lake Vui. Therefore, despite the high intensity of eruptive activity, the  $\sim 57 \times 10^6$  m<sup>3</sup> of water did not trigger any lahars. Instead, the water volume progressively diminished through evaporation, facilitated by the elevated thermal energy from the eruption. This process reduced the risk of water being expelled from Lake Vui. Hence, the numerous lahars observed during and after the 2017-2018 eruption were induced by the remobilisation of the ash deposits caused by rainfall (Fig. 2).*

3. "Metre-sized boulders" rather than metric boulders.

### **Resp.**

We modified the text:

*The particularity of the Waluembue lahar is the significant remobilization of large boulders, some up to a metre in diameter, toward the coastline, ultimately contributing to seaward shift over 50 meters. This contrasts with the formation of new beaches in other areas primarily composed of black sand. Notably, within the site, meter-size boulders are mainly found in the upstream part of the village, closer to the mountain, while decimeter-sized boulders are prevalent on the beach.*

4. Clarify. Presumably most lahar deposits are not boulder-bearing as the pyroclastic material source does not contain boulders. Hence these boulders must have come from a different source, here inferred to be the landslide.

**Resp.**

We agree and it is towards that conclusion that we direct our discussion.

5. It's probable that erosion by the lahar triggered the landslide by lateral bank erosion. I've seen this occur at other volcanoes.

**Resp.**

We complete our conclusion with this erosion on the bank – thank you

*Therefore, the most likely scenario for the Waluebue event involves a landslide initiated by lateral erosion of the banks by a lahar.*

6. Fig 2: The second pair of figures is unnecessary as they are very similar to the first two.

**Resp.**

We agree – the second pair of pictures were removed.

7. Fig 3: could all the storm tracks be combined on a single map and distinguished by colour and/or symbol?

**Resp.**

The figure is modified as suggested

8. Fig 4. These figures should be larger and labelled a, b, c etc.

**Resp.**

The figure is modified as suggested

I do wonder about the longevity of these new beaches given that the island did not have any before the eruption, despite their being other, presumably larger, historical episodes of volcanism.

**Resp.**

We recognise that longevity is a real issue as mentioned at the end of the conclusion

## Reviewer 2

This paper indicates the geomorphological changes in coastal areas after lahars associated with the eruptions during 2017 - 2018 at Ambae, Vanuatu. I agree with the significance of studies on coastal changes by eruptions and lahars. However, this paper has several shortcomings, and total revision and re-review is essential before it can be considered for publication. Furthermore, the conclusions arrived are not supported by the data presented.

### General comments

1) Although this study aims to report on coastline changes due to lahars, the overall writing style of the paper is not focusing on this point.

#### Resp.

We provide as much information as possible on these coastal changes. The phenomenon was new to local populations and had not been mentioned in previous work. We then present some of the mechanisms that probably led to these changes. Further work is welcome to support or refute our findings.

2) The data presentation is very poor. These are not systematically described.

#### Resp.

This is true, we don't have a DEM, we do not have means to quantify volumes, etc. However as mention above, the aim of this work is to report on coastal change. This is a rare phenomenon on Ambae volcano and should be highlighted. It is something this volcano is capable of doing that we didn't know about before.

a) Fig 2 shows ash-covered areas but where and when these photographs were taken is not shown. And with these photographs what the authors like to indicate is very unclear.

#### Resp.

We agree that the exact position of the photos is not indicated. However, we have mentioned approximately the direction and distance of the vent. If we refer to figure 1, we can understand that 1 to 2 km are still in the summit area and more precisely inside the caldera. But we simply want to show the thick deposit of ash at the summit. There was no such ash deposit in the caldera before the eruption. We don't see such a blanket of ash along the coastal zone, which simply indicates that the materials needed to build the new beaches came from the summit and transported through lahars.

b) Fig 3 may indicate cyclones and its paths but the relation of these climate condition with lahar generation is poorly presented.

#### Resp.

It is well known that large amount of rain after an eruption is likely to trigger a lahar. Cyclones dump large quantities of water, and those shown in the figure are no exception. With large quantities of ash following the eruption, it would be illogical to think that these rains played no part in triggering lahars. This is witnessed by local inhabitants.

c) The authors should indicate the locations of these photographs in Figs 4, 5 and 8 and on some maps. Due to lack of information, it is very unkind to readers.

#### Resp.

All the names appear on the map in Fig.7

3) The paper should be totally re-organised. In the results section, the authors describe background of the study areas and volcanoes, patchy description of 2017-2018 eruptions, previous studies and so on. These should go to a section including the introduction of previous studies and regional background before results and discussion. Description of data on lahar deposits and geomorphology is not informative. It is necessary to describe these in detail.

#### Resp.

There's no proper section on results, as can be seen on many papers, but there are also many papers that present results and discussion at the same time. This is our case too. This paper doesn't deal with the eruption, strictly speaking, so we did not develop it further.

4) Information of the eruption sequence is ambiguous. The authors imply some Plinian eruption, but when, how long did it occur, eruptions with or without pyroclastic density currents (and deposits), volume of tephra, should be presented.

Resp.

Please see answer to question 3

4) Discussion part is very poorly presented. Ideas are not supported by the data presented and logical writing. Many parts are speculative and as if it is read like an essay. What is the point of the discussion with the coastal changes by lahars?

Resp.

There is no proper discussion section but a "results and discussion" section. The presentation of this section has been improved following the recommendations of all the reviewers. The point of our results and discussion is summarized in the conclusion, "On Ambae, lahars can result in the creation of new beaches".

5) English expression should be modified and improved.

Resp.

This has been improved.

Individual comments

<Introduction>

Comments: The authors present the general statement on lahars and hazards, which do not link to the present study's focus on the coastal changes.

Resp.

We think the general statement on lahars is well placed in the introduction. It's true the hazard aspect is not the focus of this study however, it is one aspect lahars are often associated with, and we thought it was worth mentioning up front.

Comments: In the last parts "Nonetheless, there is currently no documented evidence to our knowledge that extensively highlights widespread changes in coastal morphology associated with lahar deposits. Here, we present a case where lahar deposits have profoundly and permanently transformed the coastline following the major 2017-2018 eruptive event on Ambae". The authors should search and study more on related topics and previous studies. At least examples of Santa Maria, Guatemala (Kuenzi et al., 1979) and Chaiten 2008-2009 eruption, Chile (Pierson et al., 2013; Umazano et al., 2014) reported coastal geomorphic changes after eruptions and lahars. This means all of this introduction should be rewritten.

Resp.

We have edited the introduction, added new references and removed the sentence mentioned.

"even occur outside eruptive events,..."

Comments: "outside" should not be used for temporal meanings. The word is rather for spatial things.

Resp.

Changed to "even occur independently of eruptive events..."

"Takahashi 2007"

Comments: Takahashi deals non-volcanic, general debris flows and hyperconcentrated flows. Refer appropriate reference.

Resp.

We do not agree – lahar is also a debris flow.

"particularly following landslides (Vallance 2005)"

Comments: Is this landslides of non-volcanic or volcanic? Please write clearly.

Resp.

Lahars can be syn-eruptive or post-eruptive and can even occur independently of eruptive events, particularly following landslides (Vallance, 2005). This landslide happened following the major 2017-2018 eruptive event on Ambae, so yes it is partly of volcanic origin.

"lahars can travel up to 20 km"

Comments: lahars can travel more distance. And add a reference(s) in the end of the sentence.

Resp.

We agree, the text has been modified and a reference is added : "Depending on the volcano's morphology and the triggering mechanisms, lahars can travel to more than 20 km from a volcanic summit (Pierson et al. 2014)"

<Ambae volcano and its major eruption in 2017-2018>

"is a shield volcano"

Comments: repetition

Resp.

This has been corrected.

"Discrepancies arise concerning the magnitude of this most recent eruption. Some researchers propose a Plinian eruptive event (Moussallam et al. 2019), while others suggest a lower intensity (Malinina et al. 2021)"

Comments: This is value. You cannot compare eruption style (Plinian) with intensity.

Resp.

Plinian generally indicate high intensity event

"there is a consensus that it constituted a significant event, unfolding from 5 September 2017, to 5 August 2018"

Comments: Did the Plinian eruption continue so long time duration? Please show more information about the eruption(s).

Resp.

Please see answer to question 3

"the once-dense vegetation"

Comments: revise as dense vegetation before the eruption

Resp.

This has been modified as suggested – thank you

"a lunar-like landscape"

Comments: unclear. rewrite

Resp.

Changed to "transformed into a desolate landscape, devoid of vegetation and covered in thick layers of ash deposits"

"the once-dense vegetation was transformed into a lunar-like landscape"

Comments: English expression is unclear. vegetation cannot transform to landscape.

Resp.

Changed to "the dense vegetation before the eruption was transformed into a desolate landscape, devoid of vegetation and covered in thick layers of ash deposits."

< Methodology >

"empirical data on the deposits"

Comments: what kind of empirical data should be indicated.

Resp.

Factual information obtained through observation during a survey: pictures were taken during field observation, as indicated in the text.



"by other satellite sensors"

Comments: what kind of satellite sensors? please indicate clearly.

Resp.

There are many discussions on social networks about the eruption with shared satellite data. We have now provided a link for reference in the main text.

<Results and discussion>

<Genesis of lahars>

Comments: This section is not based on the obtained results by the present study. Many of these parts should go to the background section.

Resp.

We do not agree. Giving some context helps discussing and comparing our results to that of other studies.

Comments: Why the Kelut, Indonesian example is suddenly appearing in this section? It is unclear.

Resp.

To clarify, we modified the text and the corrected version better reflects the supposed threat to the inhabitants.

"Scanty information"

Comments: Revise to "Few information"

Resp.

The text is modified as suggested

"This raises the possibility that the 1870 and 2017-2018 lahars were induced by different phenomena. (Bani et al 2009a) proposed that the outflow from Lake Manaro Lakua could be the triggering factor of the 1860 event."

Comments: These are unclearly written. Logical writing is necessary.

Resp.

The text has been modified to: "Indeed, Bani et al. (2009a) proposed that the initiation of the 1870 event might have been due to the overflow from Lake Manaro Lakua, potentially unrelated to a volcanic eruption."

"The numerous lahars observed during and after the 2017-2018 eruption were induced by the remobilisation of the ash deposits caused by rainfall"

Comments: Why the cause can be constrained to rainfall? Explain it logically.

Resp.

We see no other triggering mechanism. No lahar was observed without rainfall.

<The coastline extension induced by lahar deposits>

"The persistent presence of newly formed beaches following the 2017-2018 eruption of Ambae has created opportunities for enticing tourism development on the island."

Comments: This sentence is unnecessary.

Resp.

We do not agree – this sentence reinforces the fact that this is a widespread phenomenon and that the beaches are resisting the aggression of the sea.

"rainfall quickly transforms into lahars,"

Comments: Consider English expression. rainfall cannot transform into lahars. Rainfall may trigger lahars.

Resp.

Sentence has been modified: "transforms" is now changed to "leads".

"push the seawater offshore"

Comments: Revise English expression.

Resp.

Sentence has been changed to "...shift the coastline towards the open sea". We also adjusted the title of the paper.

"have also continued to increase in size"

Comments: how? and why? Please explain more.

Resp.

The following sentence is added as a brief explanation: "...as large quantity of ash remains at the top of the volcano."

< Ash deposits influencing the distribution of lahar deposits >

"At least nineteen (19) distinct lahar deposits of varying sizes were identified and mapped (Fig.7)"

Comments: The distribution of lahars is not clearly shown in the figure. The lahar numbers do not correspond with the numbers of lahar flow paths in the figure.

Resp.

We focus mostly on lahar deposits not on lahar events. We don't know how many lahars events have occurred and it is impossible to come up with a correct figure.

"It should be acknowledged that the estimated surface area does not include lahar deposits along the flowpaths."

Comments: Why the authors do not include lahar deposits along the flowpaths?

Resp.

Because of the difficulties of access, and precise deposits along flowpaths could not be mapped using satellite images (on google earth) because of cloud, vegetation density and spatial resolution of the images. It would have been interesting to have an idea of upstream lahar deposits, but this will not change the points made in this manuscript.

"Although precise mapping of the ash deposits was not conducted, it is evident that the eruption phases were accompanied by significant ashfall events."

Comments: Why it can be concluded? Need more logical explanation.

Resp.

Field observations were made at the summit and thick ash deposits were observed. The extension of the new beaches is another explanation.

"The December 2017 image clearly depicted ash extending from the summit crater lake and covering the western areas. January 2018 imagery revealed ash coverage across the entire summit region. By May 2018, ash deposits were observed to have extended further toward the northeast and southwest regions. In July 2018, successive ash releases were recorded by Hinemari and Terra Modis, culminating in a substantial ash discharge that blanketed the whole island on 27 July 2018. Superimposing these ash distributions, it becomes evident that the western part of the summit received the highest concentration of ash. This area coincides with the starting points of the flowpaths leading north to the Loone Lakua area and south to the area between Loone Ngwaravu and Redcliff."

Comments: The authors should indicate these on maps. This is unkind to readers.

Resp.

These sentences essentially describe figure 7. We agree, however, that figure 7 is not mentioned. This is now corrected – thank you

"This discrepancy may explain the lower occurrence of lahars and the absence of new beaches on the southeastern part of Ambae."

Comments: The authors says "lower occurrence of lahars", however, according to the figure, there are many lahars in the southeastern part. Also, the authors conclude the reason of absence of new beaches on the southeastern areas is due to the small presence of lahars. I do not agree with this point, because they do not mention about the presence/absence of PDC deposits, vegetation difference, tephra thickness for primary eruptive information and how disturbance occurred in upstream areas, as well as precipitation difference between regions. Moreover, even if the sediment introduced to the coastal areas, wave actions can erode

the lahar deposits reached to the area. The authors should discuss about these points for functions of formation and preservation of beach sediments. Otherwise, their conclusion is just speculation.

Resp.

Thank you for this comment. Our sentence about "lower occurrence of lahars" is based on interviews of people who live in the south-eastern part of the island who have not witnessed any large-scale lahars susceptible of making new beaches.

<Waluembue Case - a lahar paradox>

"decametric-sized blocks"

Comments: do you mean blocks in 10s of meter size, or do you mean decimeter-sized one (10s cm size)?

Resp.

It was an error and now modified to "decimeter-sized boulders" – thank you

"This sorting pattern reflects a decrease in flow energy from the village entrance to the beach and suggests that the blocks originated not from the island's higher elevations but rather from a location in close proximity to the village."

Comments: Please describe "this sorting" in detail. And please explain logically (such as mechanics and lithology of blocks and so on) why this sorting can indicate the source of blocks.

Resp.

We add the following paragraph: "Such arrangement of blocks is determined by various factors, including their size, weight, shape, gravity, velocity, and the terrain. As a result, on a given slope, smaller blocks tend to be carried to greater distances from the source, whereas larger and heavier boulders are often deposited closer to the origin. Thus the large boulders at the village entrance suggests that they came from an area close to the village".

<Conclusion>

Comments: Conclusion should be led by the findings of present study, not by the previous studies.

Resp.

The context and results that we cite from previous studies bring to light something we have neglected in the past.

"The steep slopes (20-25%)" and in page 4 also

Comments: Please write more details of the longitudinal profile of rivers/slopes. Is the gradient of slopes? or riverbed? All segments of upstream, midstream, and downstream have the similar steep gradient? Or these steep gradient only occur in upstream areas? Need more explanation.

Resp.

The slope encountered on Ambae's flank varies between 15% and 45% in the main lahar flow zones to the north and south of the island. Slopes of 20-25% correspond to an average range. We now refer to this in the text. The slope of the flow path is assumed to be equivalent to the slopes of the flanks.

In many parts of the texts

(Cronin et al., 2004) identified..., when the reference comes to the first of the sentence as a subject, write Cronin et al. (2004) or bring them to the end of the statement as reference.

Resp.

Citations are now correctly formatted.

Fig. 1 Ambae is the largest volcano in Vanuatu located in the northern part of the archipelago. It is a basaltic volcano that hosts three lakes on its summit, including Lake

[Click here to access/download;Figure;Fig1\\_Ambae Location\\_tiff.tif](#)

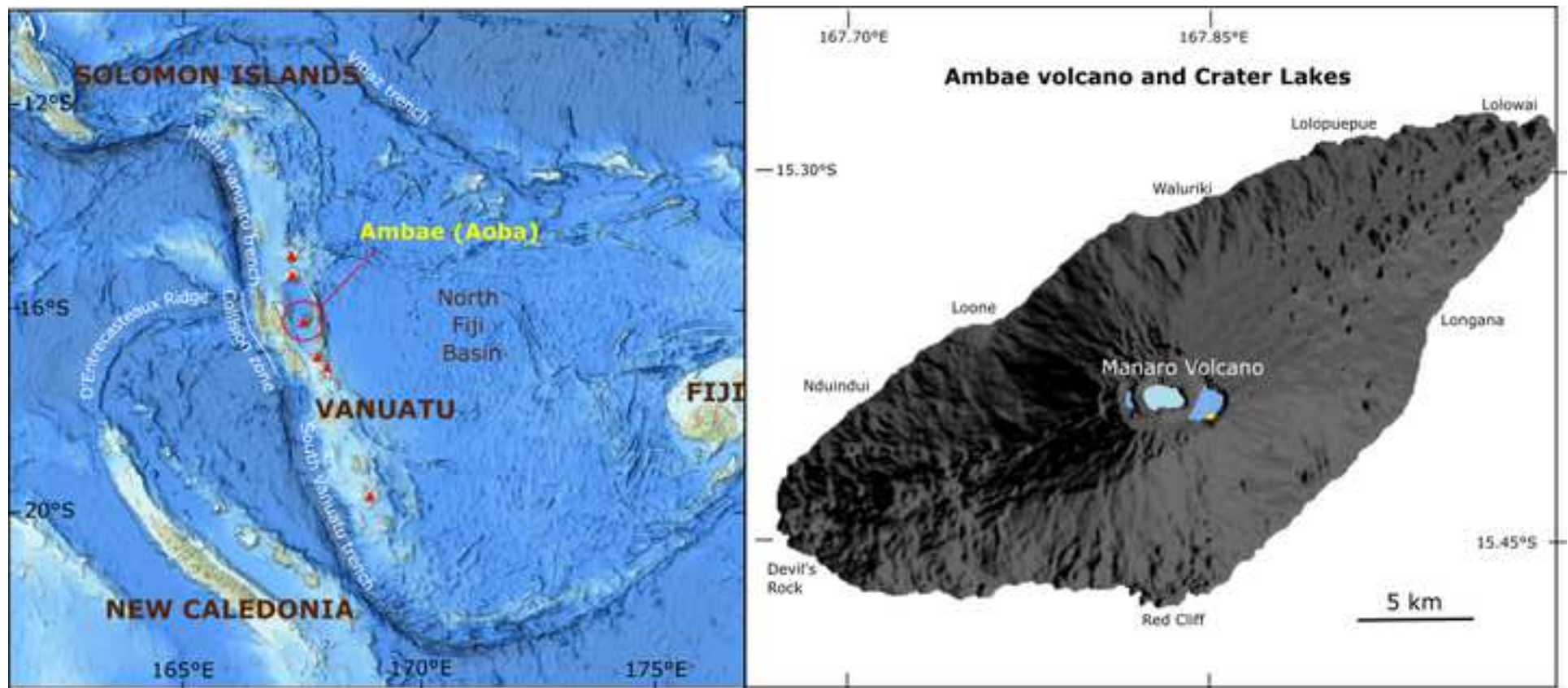


Fig. 2 Pictures of ash deposits at the summit of Ambae volcano. The entire vegetation was effected by the ash fall.

[Click here to access/download;Figure;Figure\\_2.png](#) 



Fig. 3 The trajectories of the tropical depressions and tropical cyclones between Jan. and Apr. 2018 that produced heavy rainfalls that triggered the lahars. Tracks are

[Click here to access/download;Figure;Figure\\_3.png](#)

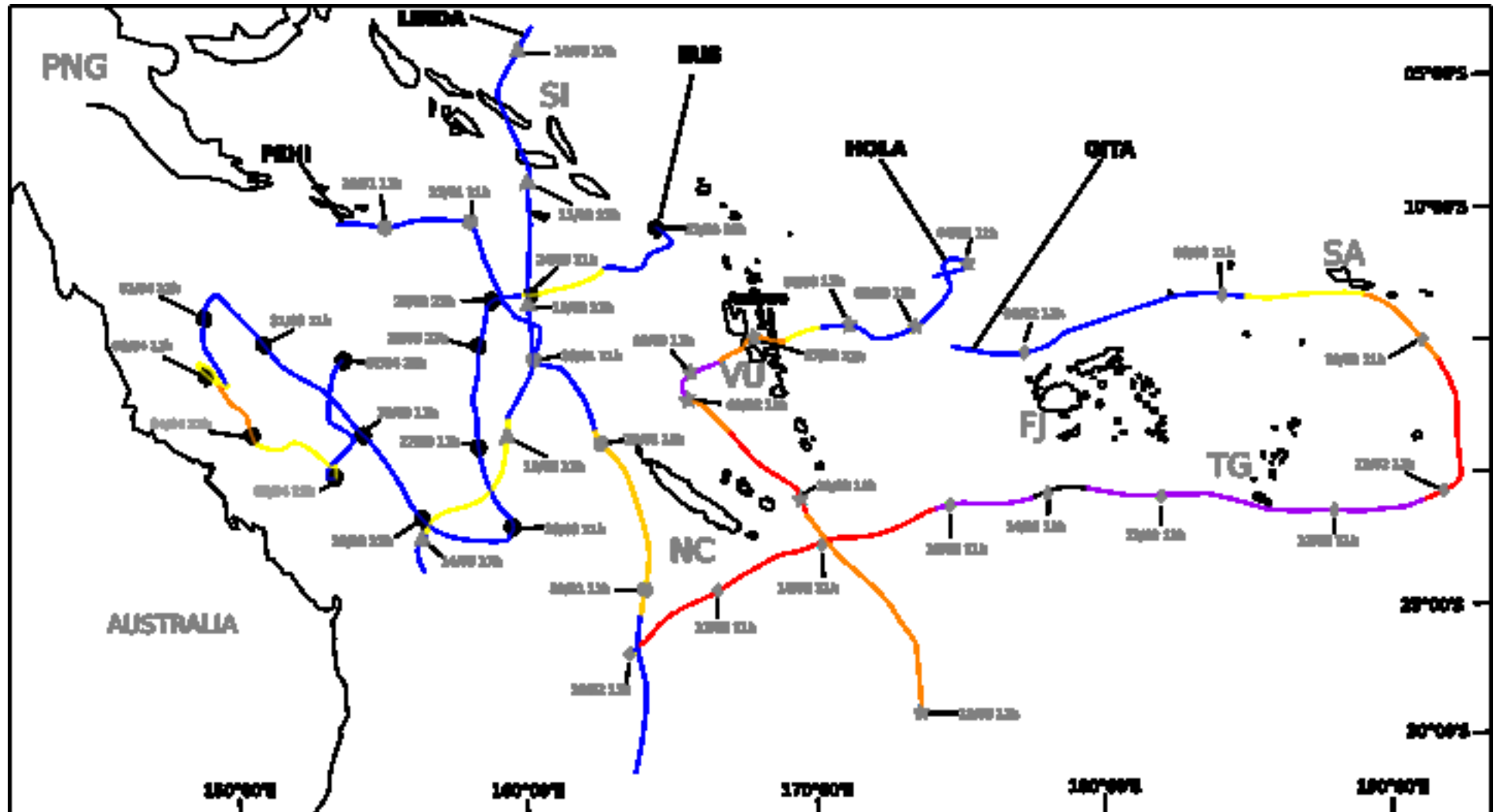
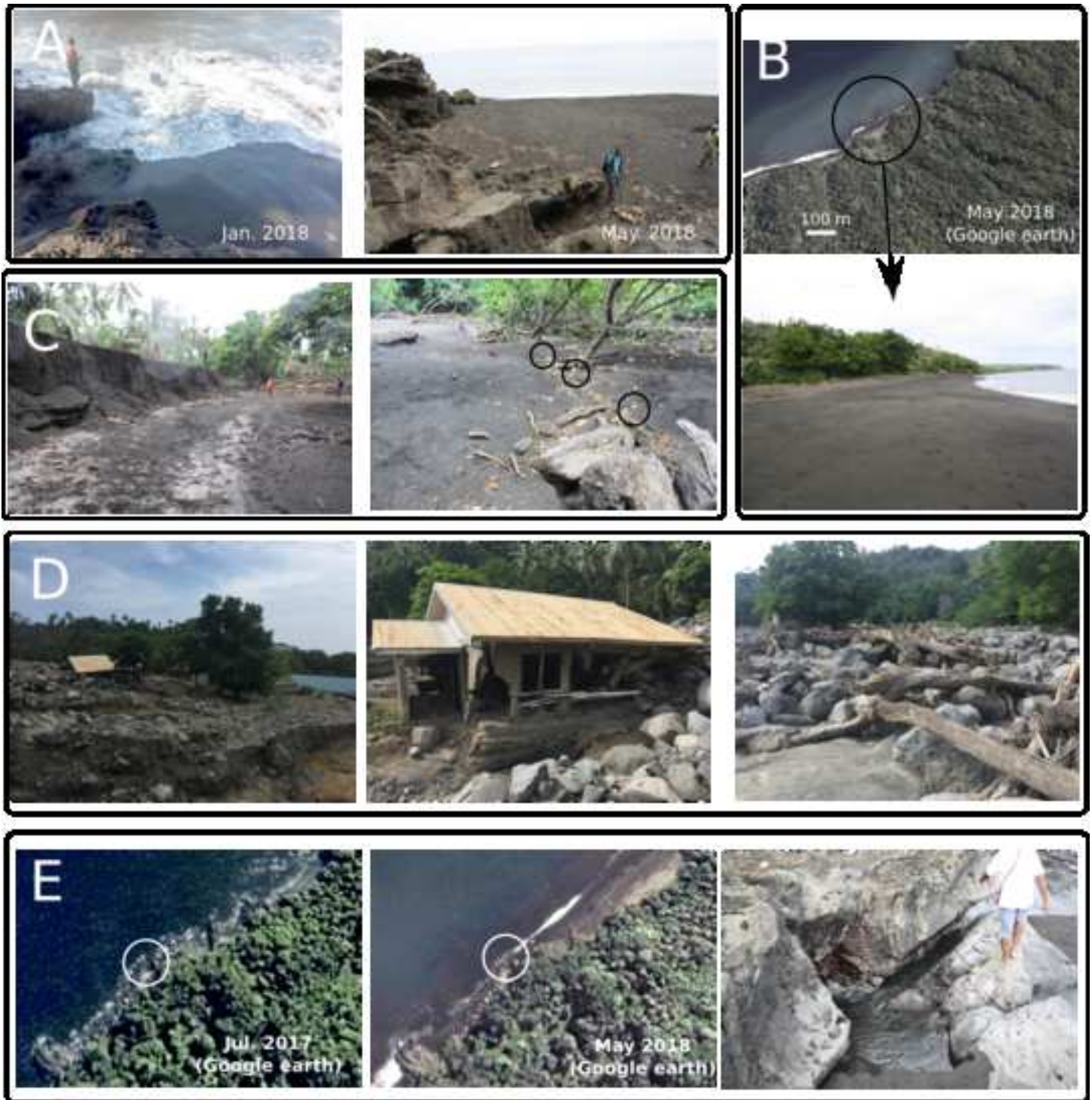
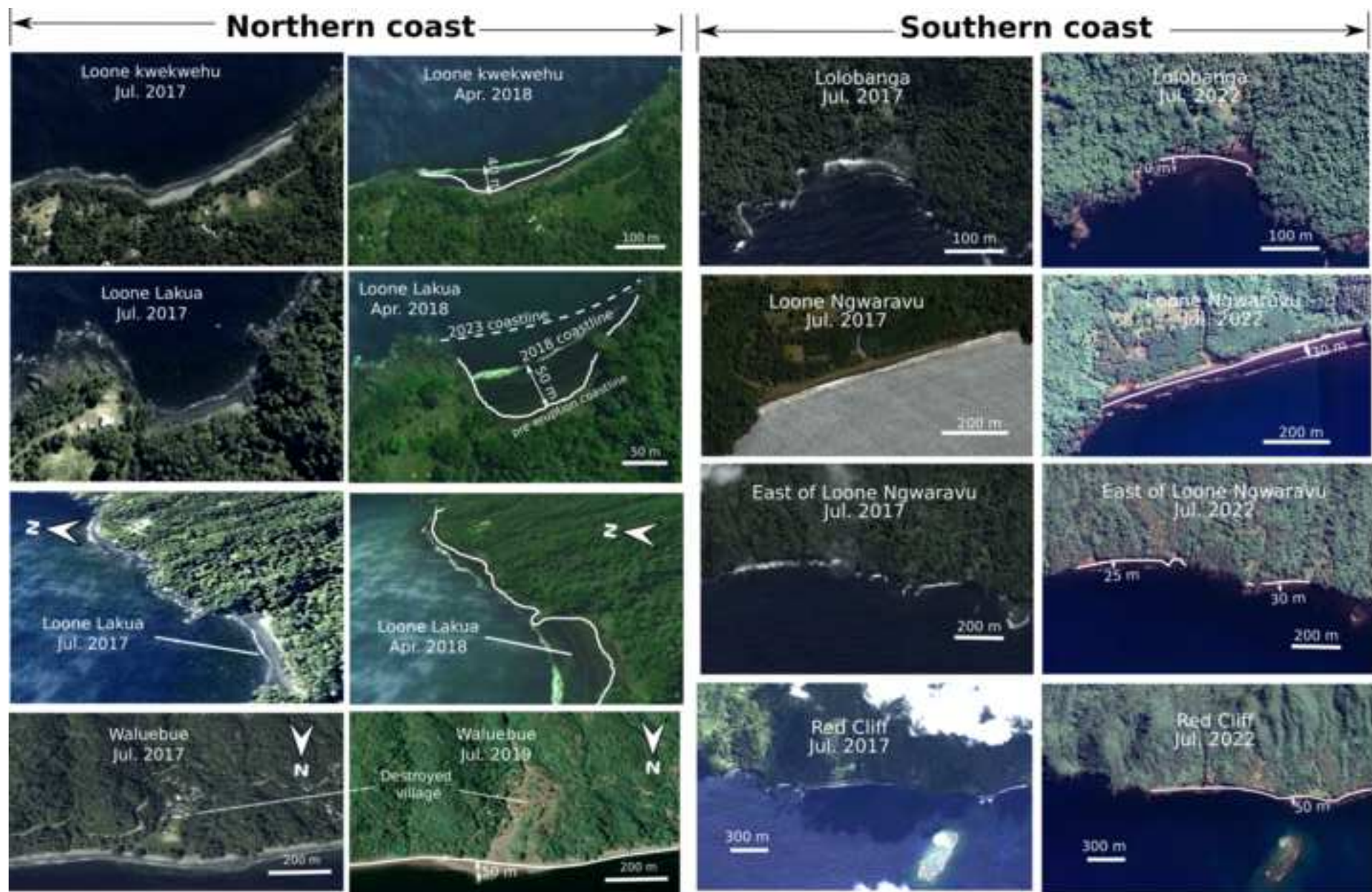


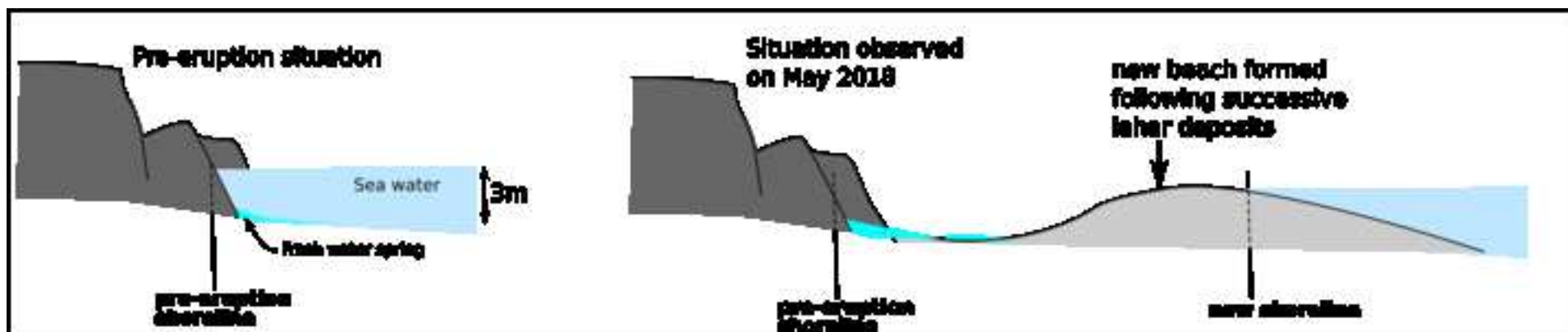
Fig. 4 Lahar deposits and impacts observed in May 2018 after the cyclones. None of these phenomena have been observed in the

[Click here to access/download;Figure;Figure\\_4.png](#)









**New water source of Loone Lakus**



**New water source of South Ambau**

Fig. 7 Distribution of lahar deposits along the coast of Ambae. The vignettes give slightly more detail on their distributions. The lahar

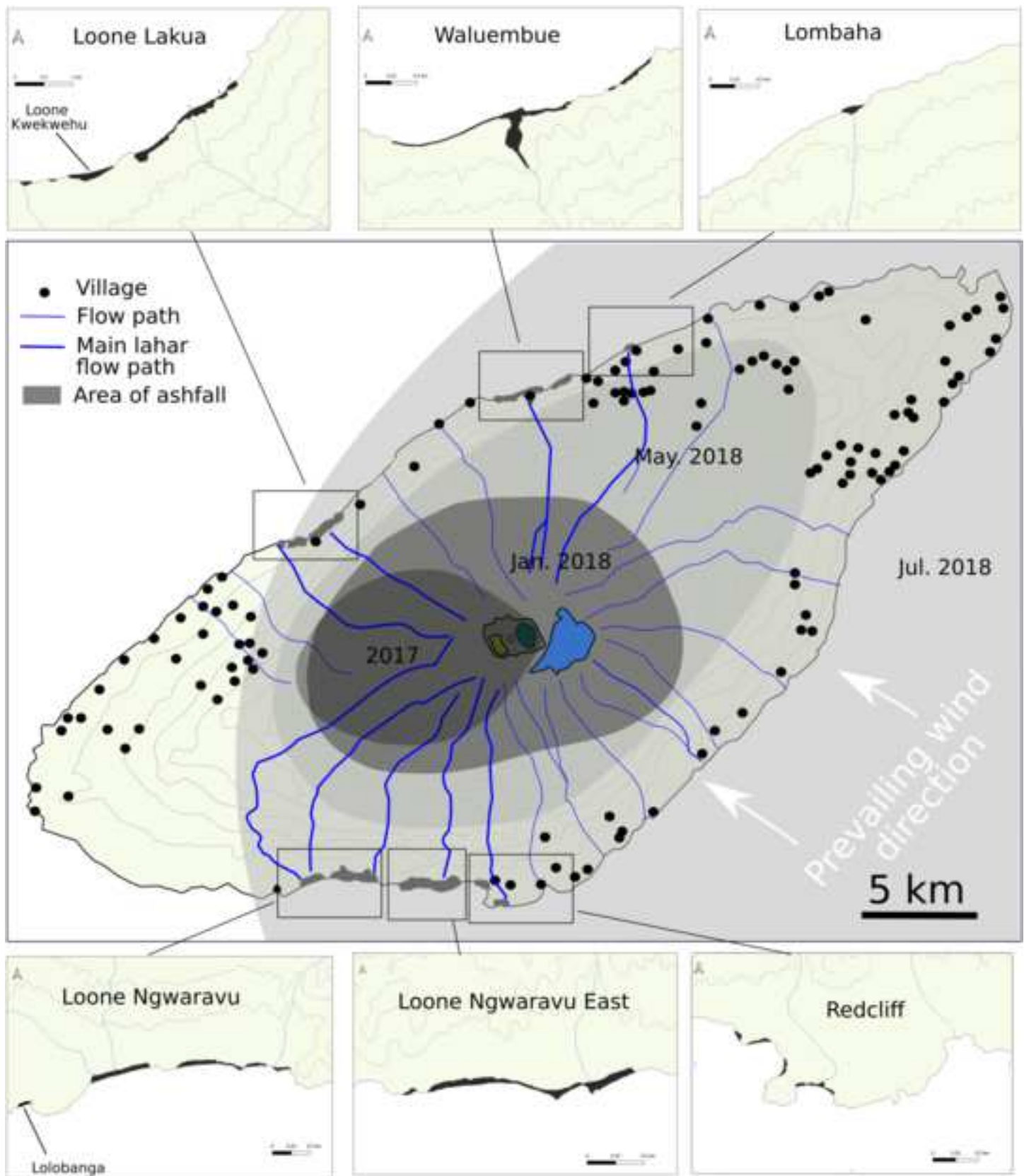


Fig. 8 Two satellite pictures (from Google Earth) showing the situation at Waluembue village before and after the lahar event. A new flowpath was enhanced by the lahar.

[Click here to access/download;Figure;Fig8\\_Waluembue before-after\\_lahar\\_tiff.tif](#)

