Editor Decision: Reconsider after major revisions (further review by editor and referees) (09 Jun 2020) by Giovanni Macedonio

Comments to the Author:
I wish to thank the reviewers for their comments and suggestions. According to the comments of the reviewers and the authors' answers, I invite the authors to submit a revised version of the manuscript. Moreover, I have a concern regarding the publication of the material already submitted for publication on another journal (Table 1 and Figure 1). It is quite unlikely that published figures can be best re-used for publication. In this case there should be a proper citation along with the figure, but if it is not necessary the respective figure/table should be left out and referred to as a citation. Else, the figures should be changed so that they fit the needs of the manuscript, to avoid possible self-plagiarism.

Resp.
A new version of the manuscript is now provided, taking into account all the corrections, suggestions and comments from the two reviewers. Please be informed that the separate paper reporting on the anomalous CO_2 content in Awu's gas was declined for publication in GRL. The topic and study are of interest, but there remains important question as to the validity of the conclusions, especially given the short time window where gases were measured and the lack of evidence for that window being representative of the long-term behavior of the system. The paper will be re-submitted as additional data highlight acquired 15 years earlier highlight the some conclusion. **The new version of the CO2 manuscript will no longer include the figure 1 and the Table 1. It is more appropriate that they appear in this NHESS manuscript.**

Reviewer 1: Corentin Caudron

Q1
The introduction just documents past eruptions. It would be interesting to briefly introduce your aim and which methods you're going to use in this study in a paragraph or two? It would be great to provide more information regarding this relatively poorly known area of the world in terms of tectonic settings and volcanic activity. I would also perhaps even a create a separate section for the volcano history.

Resp
Tow sub-sections are introduced in the introduction as suggested, including the "**1.1 Geological setting"** and the "**1.2 Historical activities**".

Q2
Going through the very interesting table 1, I noticed that eruptions are particularly short (a few days). You often refer to Kelud to interpret your results and understand the hazards at Awu which seem totally relevant to me. In our recent paper (Caudron et al., 2015, GRL), we noticed that Kelud had very short but intense eruption and hence reasonable VEI (4). Do you think this is the case at Awu? Any way to compute the intensity along with the VEI which may better reflect explosivity?

Resp
There as lack on information, particularly the mass discharges and plume heights, thus computing intensity would be difficult without speculating. We however agree on the short duration events and have added Caudron et al. (2015) for reference.

Q3
As clearly stated in the paper, another manuscript is being considered for publication in GRL. It would be interesting to explain how they differ as 1 table and several figures are found in both manuscripts (https://www.essoar.org/doi/pdf/10.1002/essoar.10501997.1).

Resp
Yes there is another manuscript on Awu submitted to GRL in which the location figure, the crater figure and the table of eruptive history is the same. But in contrast the manuscript considered in NHESS, the GRL manuscript focuses on the gas emission on Awu and more specifically on the abnormal CO_2 emission.

Q4

L.167-169: I'm a bit lost here. You basically explain that 27 MW of radiant flux would be sufficient to evaporate all the incoming water (without infiltration) in maximum 8 hrs. This is convincing but why is this coherent with the drying out prior to the 1992 eruption? We don't know how fast it did evaporate since there is no date mentioned in Table 1, and the volume was more than 18 times larger than the one you mention on l.155. Similarly how does that support the drying out prior to the 2004 eruption? You may expect more heat to be transferred to the system prior to eruption but I'm a bit lost concerning the take-home message here. The section title Transition of heat to the surface controls the water accumulation is confusing to me at this stage. The fact that you did not observe any water in 2015 could simply be explained by the evaporation am I right? So the water accumulation is not simply controlled by heat coming from below.

Resp

Thank you for this remark. We change the section title to avoid confusion. The new sub-title is **"The heat transfer to the surface controls the water accumulation".** However, given the high annual rainfail of 3500 mm, and the 3.5 million cubic meter of water in the crater, the solar heating, combined with the heat provided by the atmospheric radiation may not be sufficient to evaporate out the 95 % the lake water. Thus the heat input from a shallow magma may contribute to the evaporation.

If the increase of heat flux can lead to water lake evaporation, the cooling of the crater surface can in contrast will allow water to accumulate. Hence with the current cooling trend in the crater, one would expect that ultimately the heat supply to the surface will no longer sufficient to dry out the incoming water from the rainfall. Water may then accumulate to form a new crater lake, as already seen in the past.

Q5

L.179: I don't understand what supports the statement regarding lava domes emplacement without explosive magma-water interactions?

Resp

By the time it reaches the surface the viscous lava could be as hot as 600°C. Thus if water come into contact with such hot magmatic body one can expect explosive magma-water interaction. However, during ascent, the crystallizing magma may release much of its gas and the carapace surface temperature can rapidly cooled below 100°C once reached the surface (Sherrod et al., 2008). In such scenario the dome may passively emerged through a crater lake without explosive magma-water interactions.

Q6

L.186-187: this is wrong. The 2014 Kelud eruption occurred after 7 years following the dome emplacement. Question: my understanding was the dome quickly grew at Kelud, within a few months or so, then completely stop growing? Is it the case for Awu?

Resp

Thanks for this remarks. We now reformulate the text to better express delay between dome emplacement and violent eruption. Yes the dome has rapidly reached its current size then completely stop growing. This is now mentioned in the text.

Q7

L.196: other mechanisms exist. Just to keep the parallel with Kelud, Cassidy et al. 2019 (G3) suggest internal triggering: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018GC008161. Another may relate to permeability reduction due to alteration at dome-forming volcanoes (Heap et al., 2019). I feel you should discuss these options in detail taking into account their knowledge of the Awu system.

Resp

Other mechanisms that can trigger explosions are now included into the manuscript as suggested, including the second crystal nucleation and rapid crystallization of a degassed magmas, as well as the reduction of lava dome permeability with the hydrothermal processes.

Q8

L.215-220: this message is an important one but need to be supported better. You seem to imply that the explosivity of the past vigorous eruptions is related to magma water interactions. Am I right? The example of Kelud 2007 vs 2014 shows that the water had only a negligible effect on the explosivity. Could you comment/elaborate on this?

Resp

The similarity that we highlight between Awu and Kelud focuses on the passive emplacement of the lave dome through crater lake and the time delay between the dome emplacement and the VEI 4 eruptions. In contrast we consider that there was a coexistence of crater lake and lava dome when the VEI 4 eruption occurred on Awu which is not the case on Kelud. The triggering mechanism of kelut 2014 eruption was the second crystal nucleation event and it was the subsequent rapid crystallization at shallow depth that led to over-saturation of the source with intense diffusion of volatiles and growth of bubbles. That part is beyond the scope of our work and thus we simply quote the common process – the injection of a new magma – as the triggering event. Thanks for the remark, we now include in the manuscript other mechanisms that can trigger the eruptive activity on Awu, including the second crystal nucleation and the acidic-sulphate alteration processes.

Minor questions
L.24: what is a little know volcano?
It should be little known - thanks

L.28: what are global impacts? L.40: It would be interesting for the reader to explain why/how some injections in the stratosphere lead to a cooling while other produce a warming. Just in 1-2 sentences
In general massive sulfate aerosols injection into the stratosphere, increases the stratospheric aerosol's optical depth leading to a reduce of surface temperature. However, major tropical eruptions can produce asymmetric stratospheric heating (Robock, 2015) that can ultimately enhance warming on some regions and cooling on others.

L.75: was the Multi-GAS deployed on the dome? The arrow on figure 2. You mention different locations in the text but there is only 1 arrow in the figure.
Thanks for this remark – indeed we deployed the multi-GAS on 3 points but only one of them is consider less diluted that we consider more representative of the system and presented in this manuscripts. The manuscript is now adjusted.

L.101: this low frequency is interesting. What would create a 0.3 Hz pulsation? Are there other peaks at other frequencies?
This figure is provided to highlight the dynamic of the degassing. The mechanism behind is not developed here as it is beyond the scope of this work.

L.159: what is the ambient temperature considered?
There was no available meteorological data for Awu summit, thus 16°C obtained with the IR is used as ambient value. It is now indicated in the text.

L.187-188 : which volcano are you referring to?
The sentence refers to Awu 1992 eruption and is now better referenced.

Technical Corrections L.26: reference for the extension to the sea bed is missing
thanks – a link is added for reference (www.opendem.info)

L.44: casualties – corrected

L.97: it should be Figure 4 - corrected

L.129: Cashmana? - corrected

L.133: order of references? - corrected

L.136: It is also - corrected

L.168: will no longer be sufficient - corrected

L.176: the Kelud crater lake was not huge (2 million m3). - corrected

L.176-177: But it is - corrected

l.193: destabilize - corrected

L.195: megapascals - corrected

L.206: suggestion: rephrase this sentence. ‘arc. 18 eruptions occurred over the last 3.5 centuries, including: : :’
- corrected

L. 208: Earth - corrected

Table 1: 1892: Why do you capitalize Tsunami and Pyroclastic here? And you don’t use bold style for the number of victims. Make sure to be consistent throughout the table - corrected

Figure 1: Great figure. There is a A, but no B or C. A color scale is missing for the3D map on the right side. The bold labels on the map are a bit hard to read. - corrected

Figure 6: can’t find the GVP, 2013. I’d would also use consistent label sizes and perhaps change the white color to black for the 28/07/2015 photo. - corrected

Figure 7: typo: circulations

Revewer 2: Caroline Bouvet de Maisonneuve

Main Questions (MQ)

MQ 1: In the introduction, please provide more information about the purpose of this study and the focal point of the manuscript.

Response:
The objective of this manuscript is to highlight the intense eruptive character of Awu volcano and provide insights into the possible mechanisms that fueled the deadly energetic eruptions. We thus adjust the title to better reflect the objective of this work. The title is changed to “**Insights into the recurrent energetic eruptions that drive Awu among the deadliest volcanoes on earth**”.

Did you compile all the info in Table 1? If so, it would be worth highlighting explicitly.

Response:
Yes we did and now mention it in the text.

MQ 2: Why did you obtain whole-rock analyses? Was it just to know the average composition of Awu lavas (assuming that the current dome is representative), or was it needed to compute gas ratios?

Response:
The bulk rock analyses are intend to provide an idea about the lava dome composition and also to provide readers with as much information as possible about this little know volcano.

MQ 3: Why did you analyse the volatile flux and gas ratios, i.e. how does it fit with the rest of the data presented here and why report it here rather than in Bani et al., submitted (what is the title and where was it submitted?)? You have to tie in these types of information a bit better to strengthen this contribution.

Response:
Gas composition and emission rates provide important information about the magma source behind the observed activity. As mentioned in the text, the prevalence of H_2S of SO_2 and the low SO_2 emission rate indicate a predominant of hydrothermal processes on Awu in the present time. The limited magmatic fluids are thus likely sustained by a degassed magma source, in accord with the low equilibrium temperature of circa 380°C. The above information indicate a continuous cooling tendency in Awu’s crater, since 2004.
As for the other manuscript (*Bani et al. submitted*), it was submitted to GRL and focuses more specifically on the CO_2-rich gas from Awu and the possible source mechanisms. In contrast, this NHESS manuscript focuses on the Awu volcano and its

intense eruptive activities. We prefer to develop fully these two topics in separate manuscripts. We now provide a full reference to the manuscript submitted to GRL.

MQ 4: The interpretation of the geochemical data is overstretched. From your 2 whole-rock analyses, you cannot conclude that the peculiar tectonic setting of Sangihe is at the origin of the recurring strong activities at Awu. There are recurring violent eruptions at other volcanoes in Indonesia or the rest of the world, which are in very different tectonic settings, and Kelud (cited in this paper as an analogue of Awu's alternating dome – explosive activity) is a good example. Please revise the interpretation, and provide more information regarding the sampling location, sample descriptions, and analytical methods.

Response:

We collected only one fresh (less altered) sample directly on the lava dome, but it was analyzed in two separate laboratories, including Laboratoire Magmas et Volcans (Clermont-Ferrand) and Pôle de Spectrométrie Océan (Brest). We now mention it in the text.

We agree that it is not reasonable to trace the magma source from one sample. However, here our result provides for the first time the composition for the current lava dome on Awu. Data from Morrice et al. (1983) and Hanyu et al. (2012), included in Table 2, are obtained from samples collected in 1978-80 and 1998. The locations of the samples are provided in Hanyu et al. (2012). The current lava dome was formed in 2004. It rapidly reached its current size then completely stopped from growing. We believe it was from the same lava body thus our result may be representative of the lava dome composition.

The triggering mechanism of the 2014 eruption of kelud was the second crystal nucleation event (Cassidy et al., 2019). The subsequent rapid crystallization that followed, has led to over-saturation of the source melt with intense diffusion of volatiles and growth of bubbles. Unfortunately investigating the triggering mechanism is beyond the scope of our work. Thus we simply quote the common process – the injection of a new magma – as the triggering event. We now include in the manuscript other mechanisms that can trigger the eruptive activity on Awu, including the second crystal nucleation and the acidic-sulfate alteration processes.

We agree that the following sentence is not justified in this manuscript:

"This particular double subduction and arc-arc collision have rendered the slab prone to melting that subsequently produces the magmatic source behind the recurrent strong eruptive activities on Awu. The mechanism also contributes to unusual slab carbon delivery into the mantle as highlighted by the extremely elevated CO_2 *(Bani et al. submitted)."*

However we still believe the geodynamic context has its role in Awu activity. The above sentence is now replaced by the following sentence: *"This particular double subduction and arc-arc collision have rendered the slab prone to melting (Clor et al., 2005) that subsequently supply the magmatic source beneath Awu volcano.*

Supplementary edit

A throughout English edit of the text was kindly provided on a separate file (nhess-202027-RC2-supplement) by this reviewer.

All the correction are integrated in the corrected version of the manuscript.

Insights into the recurrent energetic eruptions that drive Awu among the deadliest volcanoes on earth

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Abstract

The little known Awu volcano (Sangihe island, Indonesia) is among the deadliest with a cumulative death toll of 11048. In less than 4 centuries, 18 eruptions were recorded, including two VEI-4 and three VEI-3 eruptions with worldwide impacts. The regional geodynamic setting is controlled by a divergent-double-subduction and an arc-arc collision. In that context, the slab stalls in the mantle, undergoes an increase of temperature and becomes prone to melting, a process that sustained the magmatic supply. Awu also has the particularity to host alternatively and simultaneously a lava dome and a crater lake throughout its activity. The lava dome passively erupted through the crater lake and induced strong water evaporation from the crater. A conduit plug associated with this dome emplacement subsequently channeled the gas emission to the crater wall. However, with the lava dome cooling, the high annual rainfall eventually reconstituted the crater lake and created a hazardous situation on Awu. Indeed with a new magma injection, rapid pressure buildup may pulverize the conduit plug and the lava dome, allowing lake water injection and subsequent explosive water-magma interaction. The past vigorous eruptions are likely induced by these phenomena, a possible scenario for the future events.

1 Introduction

Awu is a little known active volcano located on the Sangihe arc, northeast of Indonesia. It is the largest and the northernmost volcano of the arc with an aerial volume of ~27 km^3 that constitutes the northern portion of Sangihe Island (Fig.1). The edifice culminates at 1318 m above sea level and more than 3300 m from sea bed on its western flank (www.opendem.info). The summit crater is 1500 m in diameter and 380 m depth from from the highest point. The crater flow of 260 m in diameter is currently occupied by a cooling lava dome of 30 m height and 370 m in diameter, formed after the 2004 eruption. Since 1640, Awu went through 18 eruptions, including 2 of VEI 4 (Volcanic Explosivity Index; Newhall and Self, 1982), in 1812 and 1966. Such powerful VEI 4 events represent only 5% of the eruptions in the last 10,000 years (Pyle, 2015), and curiously two have occurred on Awu with a return period of 154 years. In the database of volcanic eruption victims compiled by Tanguy et al. (1998), Awu eruptions claimed a total of 5301 victims, including 963 casualties during the 1812 eruption, 2806 during the 1856 eruption and 1532 during the 1892 eruption.

This latter database did not take into account the 2508 victims of the 1711 eruption (Van Padan, 1983, Data Dasar Gunung Api 2011) and 3200 deaths following the 1822 eruption (Lagmay et al., 2007). The latest VEI 4 eruption on Awu in 1966 killed 39 people, injured 2000 and forced the evacuation of 420,000 inhabitants (Withan, 2005). In total since 1711, Awu's recurrent eruptive activities have caused a cumulative 11048 fatalities, mainly from lahar events. Awu is thus one of the deadliest volcanoes worldwide that merits better attention. In this works we aim to highlight the intense eruptive character of Awu volcano and provide insights into the possible mechanisms i that fueled the deadly energetic eruptions.

1.1 Geological setting

The volcanism within the Molucca Sea is dominated by the unique example of the present-day arc-to-arc collision that involves the Sangihe arc from the west and the Halmahera arc from the east. The Molucca Sea plate that existed between the two arcs is currently dipping east under the Halmahera arc and west under the Sangihe arc. At least 600 km of lithosphere has been subducted to the west since its onset 20 Ma ago and on the opposite side, the Benioff zone associated with the east-dipping slab can be identified to a depth of 200-300 km (Hall et al., 1995; Hall and Wilson, 2000). This double subduction has led to the arc-arc collision that commenced around 3-5 Ma in the north of Molucca Sea and is currently considered as complete in the area north of Talaud island (Fig.1) (Cardwell et al., 1980). This is highlighted by the distribution of the 8 aerial active volcanoes only along the southern part of the 550 km of Sangihe arc. Beyond the Sangihe island, the volcanoes are inactive and dissected (Morrice et al., 1983), Awu being the northern most active volcano of the arc. Beneath the southern part Molucca Sea, the Sangihe forearc is presently overriding the Halmahera forearc, while the Halmahera arc itself is thickening by the over-thrusting of its back-arc from the east (Hall and Wilson, 2000).

1.2 Historical activities

Since the early 1980s, numerous studies have pointed to Awu as the center of strong volcanic manifestations with global impacts (Robock, 1981; 2000; Handler, 1984; Zielinski et al., 1994; Jones et al., 1995; Palmer et al., 2001; Donarummo et al., 2002; Guevra-Murua et al., 2015) although recent works have reviewed and declassified some of these events, including the 1641 event that was considered as responsible for 1642-1645 global cooling (e.g., Robock, 1981; Simkin et al., 1981; Jones et al., 1995) but later attributed to the Parker eruption of Jan. 4, 1641 (Delfin et al., 1997). Similarly, on the famous Edward Munch painting of 1893 - the "The Scream", the red sky was first considered as induced by the 1892 eruption of Awu (Robock, 2000) but was later attributed to Krakatau 1883 eruption (Olson et al., 2004) and then finally considered as inspired by the nacreous clouds (Fikke et al., 2017; Frata et al., 2018). But Awu's 1812 eruption of VEI 4 has loaded a significant amount of ash and aerosols into the atmosphere leading to the global abnormal correlation between dust load in the atmosphere and solar activity (Donarummo et al., 2002). In 1856, another eruption of Awu (VEI 3) injected massive amount of sulfate aerosols into the stratosphere, leading to an increase in the stratospheric aerosol's optical depth, sufficient to reduce the sea surface temperature and thus subsequently reduce the number of tropical cyclones (Guevara-Murua et al., 2015). In contrast, Handler (1984) indicates that the 1966 eruption of Awu (VEI 4) loaded a notable amount of aerosols into the stratosphere resulting in a warmer eastern tropical Pacific Ocean over three consecutive seasons with subsequent influence on El Nino type events. Such a regional response is typical of tropical major eruptions that produce asymmetric stratospheric heating (Robock, 2015). On the regional and local scale, Awu eruptive activities have triggered at least two tsunamis, on Mar. 2, 1856 and on Jun. 7, 1892 (Latter et al., 1981; Paris et al., 2014). No less than 18 eruptions were reported on Awu volcano since 1640, thus about 1 eruption every ~20 years, highlighted our compilation (Table 1). The latest eruption was a VEI 2 in 2004.

2 Methodology

The available documents that refer to Awu volcano, as summarized in the introduction, are generally incomplete but most point to vigorous explosions and subsequent casualties. Thus to gain more insights into Awu's volcanic activity, a reconnaissance visit to the summit was carried out in July 2015 with thermal and gas measurements. Thermal imaging was performed using OPTRIS PI400, a miniature infrared camera that weighs 320g, including a lens of 62°x49° FOV, f=8 mm and a dynamic range equivalent to the radiant temperature of -20°C to 900 °C. The detector has 382 × 288 pixels and the operating waveband is 7.5-13 µm. The maximum frame rate is 80 Hz. The camera was first positioned on the crater rim (Fig.2) observing the whole crater, then in the crater, looking at the two main hot surfaces (Fig.2). The radiant flux (Q_{rad}) estimation is obtained using the following: $Q_{rad} = A\varepsilon\sigma(T_s^4 - T_a^4)$, where A is the area of the hot surface, ε is the emissivity (0.9 for andesite), σ is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), T_s is the hot surface temperature and T_a is the ambient temperature. Thermal results are corrected for an oblique viewing angle of 30° following the approach detailed in Harris (2013) and the hot surfaces in the crater are discriminated based on their brightness temperature ranges, including 16-20 °C, 21-25 °C, 26-30 °C, 31-35 °C and 36-41 °C. Such thermal ranges allowed better estimation of the total radiant flux given the heat distribution in the crater. Values below 16 °C fall in the background level whilst 41 °C is the maximum temperature observed from the rim. Temperature values were corrected for atmospheric influence relying on ACPC (Atmospheric Correction Parameter Calculator; https://atmcorr.gsfc.nasa.gov/) and validated with closer thermal recording before integrated into the radiant flux calculation. Thanks to the high acquisition rate of OPTRIS, a few series of continuous recordings were obtained on the most heated surfaces to retrieve the heat flow dynamics.

A portable Multi-GAS system from INGV (as used by Aiuppa et al. 2015; Bani et al., 2017; 2018) was deployed to measure the gas composition. The instrument was positioned in the main degassing point at the northern part of the crater (Fig.2) and simultaneously acquired concentrations of H_2O, CO_2, SO_2, H_2S, and H_2 at 0.1 Hz. Data were processed using Ratiocalc (Tamburello 2015). The scanning DOAS was used for the gas emission budget. The instrument performed at fixed position in the crater (Fig.2). Further details on Awu gas measurements are provided in a separate paper and hereafter referred to as (Bani et al. submitted).

During this fieldwork, a less altered rock sample was selected directly on the lava dome then analyzed for major and trace elements using ICP-AES. The same sample was analyzed in two different laboratories, including Laboratoire Magmas et Volcans (Clermont-Ferrand, France) and Pôle de Spectrométrie Océan (Brest, France).

3 Results

The whole-rock composition of the lava dome, obtained from ICP AES analysis, indicates a dome composition of 52-56% SiO_2 and relatively low alkali contents corresponding to a basaltic-andesite (Table 2, Fig.3). Results are comparable with the data from Morrice et al (1983) and Hanyu et al. (2012). Trace elements normalized to N-MORB point to elevated ratios of large ion lithophile elements (LILEs), light rare earth elements (LREEs) and high-field strength elements (HFSEs) (Table 2, Fig.3).

DOAS measurement results obtained on Awu indicate a relatively small degassing with a mean daily SO_2 emission rate of 13±6 tons. The multigas results indicate H_2S/SO_2, CO_2/SO_2, H_2/SO_2 and H_2O/SO_2 ratios of 49, 297, 0.1 and 1596 respectively with the corresponding gas composition equivalent to 82% of H_2O, 15% of CO_2, 2% of H_2S, 0.05% of SO_2 and 0.02% of H_2. Assuming the above results are representative then H_2O, CO_2, H_2S, and H_2 emission rates would be 5800 t/d, 2600 t/d, 340 t/d and 0.1 t/d respectively. The gas equilibrium temperature obtained by resolving together the SO_2/H_2S vs. H_2/H_2O redox equilibria (see methodology in Aiuppa et al., 2011; Moussallam et al., 2017) is circa 380 °C (Bani et al., submitted)

Thermal infrared recording from the rim highlights two main heated surfaces in Awu's crater, but both are located in the northern part of the lower crater wall, next to the lava dome (IR2, IR3, Fig.4). It is also evident from these thermal results that the lower crater wall around the dome is much hotter than the lava dome itself. The total radiant flux from the crater (IR1, Table 4) is 27±12 MW, including 5.6±2.4 MW from the lava dome and 21±9 MW from the area surrounding the dome. The highest radiant flux per area (0.9 MW) is recorded in the IR3 zone where gas is released at a low frequency of 0.3 Hz with a thermal fluctuation amplitude of 0.1-0.3 MW.

4 Discussion

4.1 Melt source

To sustain the recurring strong eruptive activity of Awu, highlighted by one strong eruption every 20 years over the last 3.5 centuries (including two VEI 4 and three VEI 3), requires sufficient magma supply rate. The total alkaline vs. SiO_2 diagram (Table 2., Fig.3) indicates a basaltic andesite magma, typical of island arc volcanoes where the geodynamic context allows a relatively evolved magmatic source. Awu is part of the Sangihe arc where the geodynamic processes are controlled by the divergent double subduction that resulted in the Sangihe forearc overriding the Halmahera forearc (Cardwell et al.,1980, Morrice et al., 1983, Hall and Wilson, 2000; Jaffe et al., 2004; Zhang et al., 2017; Bani et al., 2018). The pattern obtained by normalizing the trace elements to N-MORB indicates high LILE (Cs, K, Rb, Ba and Sr) content and low abundance of HFSE, represented by Nb, typical of subduction melt source in which the mantle wedge has been contaminated by fluid released from the subduction slab (McCulloch and Gambke, 1991; Davidson 1996, Mcpherson et al., 2003). This result is coherent with Jaffe et al. (2004) who highlight low $^3He/^4He$ (5.4-6.4 R_A) and high $CO_2/^3He$ ratios (64-180 $\times10^9$) as well as high $\delta^{13}C$ (≥-2‰) suggesting slab contribution into the magmatic fluids at Awu. Clor et al. (2005) further point out anomalous high N_2/He (2852) coupled with low $\delta^{15}N$ (3.3%) suggesting increased slab contribution, possibly by slab melting as collision stalls the progress of the subducting plate and allows it to become superheated (Peacock et al., 1994). This is supported by the slow-down of the subduction rate as evidenced by seismic studies (McCaffrey, 1983; Pubellier et al., 1991; Zhang et al., 2017). This particular double subduction and arc-arc collision have rendered the slab prone to melting (Clor et al., 2005) that subsequently supply the magmatic source beneath Awu volcano.

4.2 A conduit plug

Lava domes are formed when viscous lava extrudes to the surface effusively then piles up around the vent. Such phenomena involve complex processes, including crystallization, bubble nucleation, growth, coalescence and out-gassing, bulk magma deformation, crack propagation and healing (e.g., Ashell et al., 2015 and ref therein). It is the competition between these processes that either promotes or prevents degassing, leading to explosions or stability of a lava dome (Klug and Cashman, 1996; Takeuchi et al., 2005; Mueller et al., 2008). On Awu, the SiO_2 content of the lava dome higher than 50 wt% as well as the perfect semi-spherical morphology of ~1.3×10^7 m^3 that extended from the middle of the crater suggests an endogenous growth that generally inflates the dome carapace through magma injection at depth. In such case, lava domes are known to induce variable porous and brecciated carapace surrounding a denser and coherent interior (Newhall and Melson, 1983; Fink et al., 1992; Wadged et al., 2009, Ashell et al., 2015) suitable to form a plug in the upper conduit (Watts et al. 2002). The radiant thermal energy around the lava dome is much higher than the heat release from the dome representing 79% of the total 27 MW from the crater. Only ~6 MW is released through the lava dome itself. It is also around the dome that much of the gas is released to the atmosphere (Figure 5). The hottest surfaces also correspond to the main degassing points which suggests that heat is rather sustained by fluid circulations around the dome. With a conduit plug, the gas released at depth is thus forced to the periphery of the lava dome (Fig.5), similar to other dome-forming systems, including Rokatenda (Primulyana et al., 2018), Lascar (Matthews et al., 1997) or Soufriere Hills (Sparks, 2003).

It is thus obvious that the existence of a conduit plug may constitute a barrier to the gas flow, suitable for rapid pressure build up with new magma injection, a situation that can strongly contribute to the vigorous explosions on Awu.

4.3 The heat transfer to the surface controls the water accumulation

Out of the 18 recorded eruptive activities on Awu, 11 were tagged as phreatic and 7 other eruptions were phreatomagmatic and magmatic (Table 1). It is thus unambiguous that water played a major role in Awu volcanic activity. Indeed, with an average annual rainfall of 3500 mm (Stone, 2010) and a crater area of 1.5 km^2, the Awu summit is likely to accommodate 5.2×10^6 m^3 of water each year. Given that there is no visible water outlet from the crater, one can expect water accumulation and strong infiltration into the hydrothermal system which may then subsequently contribute to phreatic eruptions. But as highlighted in figure 6, surface water was not always present in Awu's crater. A crater lake existed in 1922, 1973 and 1995 whilst in 1931 and 1979 a crater lake co-existed with a lava dome. In July 2015 (this fieldwork) there was no water in the crater and a lava dome occupied the central part of the crater. July is among the driest months of the year, however, the average monthly rainfall on Sangihe Island doesn't fall below 130 mm (Stone, 2010). Hence one can expect a cumulative water volume of at least 195×10^3 m^3 (equivalent to 7×10^6 moles or 1.3×10^8 g, using PV=nRT) into Awu's crater during that period of the year. But the absence of water as observed in July indicates that the water was efficiently infiltrated and evaporated away. In theory, if we assume that the infiltration is negligible, then it requires a heat energy of 8.0×10^{11} joules (using $mC_p\Delta T$; m is the water mass, Cp is the water's specific heat capacity, ΔT is the difference between boiling and ambient temperature (taken as 16°C from IR camera since no meteorological data is available) to bring the above volume to the evaporation temperature (100°C) and another 4.6×10^9 joules (using mL; L is the latent heat of vaporization) to convert it into water vapor. A total 8.1×10^{11} joules is thus sufficient to dry out the July incoming water volume. With 27 MW of radiant flux from the crater, equivalent to 2.7×10^7 J s^{-1}, only 8 hours is necessary to heat the 7×10^6 moles of water from 16 °C to the evaporation temperature and transform it to water vapor. This duration should be considered maximum as the portion of water infiltration is ignored. Nevertheless, the above simple calculation suggests that the heat transfer to the surface from the magmatic source is largely sufficient to evaporate out the water and thus the water accumulation in Awu's crater could rely on the amount of heat supply by the shallow magma body. In 1992, Awu's crater lake experienced 95% of water loss from its initial volume of 3.5×10^6 m^3 (Table 1). Although attributed with no details to a seepage through active faults beneath the crater (GVP, 2004), the decrease of water pH from 5 to 3 and the lake edge temperature of ~40°C (GVP, 1992) indicate a possible fluid supply from depth that subsequently led to the October 1992 phreatic eruption (Table 1). During such event water loss through evaporation can be non negligible. This was the case during the 1995 phreatic eruption in lake Voui where more than 14 million cubic meter of water was lost through evaporation (Bani et al., 2009), whilst the lake edge temperature was 40°C and a pH of 2-3 (Wiart, 1995). It thus likely that the heat supply by the combined hydrothermal and magmatic system has contributed to the significant water loss on Awu in 1992. Similarly, in 2004 the lake water progressively dried out before the eruption, in response to the progressive increase of heat flux that ultimately reach 38.8 MW on Jun. 8, 2004 (http://modis.higp.hawaii.edu/), much higher than the 27 MW obtained in Jul. 2015 (Table 3). If the increase of heat flux can lead to water lake evaporation, the cooling of the crater surface can in contrast allow water to accumulate. Hence assuming that the current cooling trend in Awu's crater continues, then ultimately the heat supply to the surface will no longer be sufficient to dry out the incoming water from the high annual rainfall. Water may then accumulate to form a new crater lake, as already witnessed in the past.

4.4 The Hazardous situation

The contact of liquid water with a hot surface is widely accepted as a process that can trigger explosive water-magma interactions (Wohletz, 1986; 2002; Zimanowski et al., 1995; Thiéry and Mercury, 2009). However, according to a review of historical eruptions through volcanic lakes, ~2% involved relatively passive growth of subaqueous to emergent lava domes (Manville, 2015). This was the case at Kelud volcano (Java) in 2007 when a lava dome emerged in the middle of a crater lake creating a threat of a major eruption. But the vigorous explosion never happened as suspected (Hidiyati et al., 2009). Only 7 years later, in 2014 a VEI 4 eruption was witnessed at the same volcano (Kristiansen et al., 2014; Caudron et al., 2015). Such a delay between dome occurrence through crater lake and major eruption was also witnessed on Awu in 1996 where a VEI 4 event occurred 35 years after the lava dome emplacement (in 1931). The same scenario was repeated in 1992, when an eruption occurred 13 years after another lava dome passively erupted through the crater lake. It is thus likely that during ascent, the crystallizing magma has released much of its gas and the carapace surface temperature has rapidly cooled below 100°C once reached the surface (Sherrod et al., 2008). In such scenario the dome may passively emerged through a crater lake without explosive magma-water interactions. In 2004, the lava dome formation on Awu differs from the past dome emplacements. There was no crate lake and its growth constituted the last event of the 2004 eruptive event. In less than two weeks the dome reached its current size then it completely stopped from growing. Hence, whatever the scenario is, lava dome emplacement on Awu did not immediately trigger eruption. Furthermore, the current cooling lava dome on Awu was developed on a flat crater floor which is more than 350 m below the crater rim. The chances to witness a dome collapse on Awu are thus negligible in contrast to other lava dome emplacements, were the average growth rate is approximately 10^4 m^3 day^{-1} with a mean volume of $5x10^7$ m3, some with unstable slopes (Newhall and Melson, 1983). The hazardous situation on Awu is rather related to the presence of the conduit plug and a crater lake since this latter may further increase the potential of violent eruptions (Sheridan and Wohletz 1983; Wohletz 1986). Based on the size of Awu's lava dome, the subsurface volcanic system has to develop more than 3.1 MPa of pressure (Pressure (Pa) = F/Area (m^2); F (N) = masse (kg) x 9.8 (m/s^2); density of 2700 kg/m^3) to destabilize the $3.5x10^{10}$ kg of lava dome. However, given that tens of mega-pascals can be easily developed in the conduit or reservoir (e.g., Gudmundsson, 2012), there is no doubt that the system will clear-up the conduit and pulverize the lava dome in the future, as already witnessed in the past. The common process that drives eruptive activity is the injection of a new magma into a subvolcanic reservoir (Pallister et al., 1991; Williamson et al., 2010). Indeed, besides adding volume that increases the overpressure of the magma on the confining walls, the heat introduced by the process induces convection and vesiculation (Sparks et al., 1977) that subsequently mobilize the crystal-rich magmas (Burgisser and Bergantz, 2011), whilst the fluxing of volatiles increases the buoyancy (Costa et al., 2013; Williamson et al., 2010; Parmigiani et al., 2016). All these mechanisms concur to pressure buildup and eventual eruption. Alternatively, given the degassed magma source on Awu, highlighted by the prevalence of H_2S over SO_2, the low SO_2 emission budget (13 t/d) and the low equilibrium temperature of circa 380 °C obtained by resolving together the SO_2/H_2S vs. H_2/H_2O redox equilibria (Aiuppa et al., 2011; Moussallam et al., 2017), a second crystal nucleation event at shallow depth can occur (Melnik and Sparks, 2005). The rapid crystallization that follows will lead to an over-saturation of the remaining melt with intense diffusion of volatiles and growth of bubbles (Cashman, 1992; 1998; Swanson et al., 1989). The process can lead to powerful eruptive discharge that can possibly clear out the conduit plug and the lava dome. This was the mechanism that pulverized the lava dome at Kelud in 2014 (Cassidy et al.2018) and pumped out the degassed magma on Rokatenda in 2012-2013 (Primulyana et al., 2017). Another mechanism that can possibly induced eruption on Awu, given the predominant hydrothermal manifestation, is the acidic-sulphate alteration (Heap et al., 2019). This latter reduces the permeability of the lava dome which in turn promotes pore pressure increases that can eventually lead to eruption. Whatever the triggering mechanism, the future eruption will clear out the conduit plug and pulverize the lava dome, as already witnessed in the past. If such event occur in the presence of a crater lake, the large influx of water into the conduit could lead to explosive magma-water interaction. The intensity of such mechanism depends on the efficacy of the heat transfer from the magma to water which is directly correlated to the size of the contact area between magma and water. This latter is likely to increase significantly and the heat transfer rate may escalate with the conduit plug clearing. Such a great energy release may induce explosive vapor expansion, thorough magma fragmentation and subsequently the formation of convecting columns, a significant and more widespread tephra dispersal through fall and possibly pyroclastic density currents. Such events of particularly high intensity are described as phreato-Plinian eruptions and can only be explained with the involvement of surface water in the eruption dynamics (Areva et al., 2018).

The presence of sufficient water volume in the crater besides the lava dome may thus constitutes the most hazardous situation at Awu volcano (Fig.7), a possible scenario behind the past vigorous eruptions.

5 Conclusion

Awu is the northernmost active volcano of the Sangihe arc. It is the center of 18 eruptive activities over the last 3.5 centuries, some with very strong intensity (VEI 4 and VEI 3). The pyroclastic and lahar events triggered by these eruptions have killed a cumulative 11048 inhabitants of Sangihe island, highlighting this volcano as one of the deadliest on Earth. Paradoxically, very little is known about this volcano. As emphasized in this work, the regular magma supply that sustained the activity of Awu is possibly linked to the peculiar geodynamic context of the region, controlled by the divergent double subduction and the subsequent arc-arc collision. Awu also has the particularity to host alternatively or simultaneously a lava dome and a crater lake. Lava domes seem to erupt passively through a crater lake and the heat that accompanied this emplacement has shown to be sufficient to dry out the lake. The emplacement of the lava domes also appears to be associated with a conduit plug development that forces the degassing to the crater wall. With time the lava dome cools down, allowing a progressive crater lake formation with the high annual rainfall in the region. This scenario may ultimately constitute the most hazardous situation if a new magma injection occurs at depth, or the system undergoes a second crystal nucleation event within the degassed magma or the lost of permeability of the lava dome with the acidic-sulphate alteration. Indeed these latter processes may induce a rapid pressure buildup that can pulverize the conduit plug and the lava dome, creating a favorable condition for a significant water injection and a subsequent explosive water-magma interaction. Such a scenario likely resulted in the past vigorous eruptions on Awu and may occur in the future given the presence of a cooling lava dome and a conduit plug.

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Captions

Table 1. History of Awu eruptive activity. Most of the information is obtained from Data Dasar, Gunung Api, (2011) and Siebert et al. (2010).

Date	**Eruptive events**
1640 (Dec.)	Phreatic eruption (Data Dasar, Gunung Api, 2011; Siebert et al., 2010).
1641 (Jan.3-4)	Phreatic eruption, lahar event (Wichmann, A., 1893; Siebert et al., 2010; Data Dasar, Gunung Api, 2011).
1677	Phreatic eruption (Data Dasar, Gunung Api, 2011).
1711 (Dec. 10-16)	On the night of Dec. 10, violent eruption (VEI 3) propelled incandescent material above the summit. Pyroclastic flow combined with hot lahar, generated by the outburst of the crater lake, wiped out the entire city of Kandhar located at the eastern base of the edifice. About **3000** people were killed, including 2030 in Kendhar and 408 at Tahuna. Among those victims, 400 corpses were described as suffocated by the heat of pyroclastic (Wichmann, A., 1893; Van Padang, 1983; Data Dasar, Gunung Api, 2011; Siebert et al., 2010).
1812 (Aug. 6-8)	Large phreatomagmatic eruption (VEI 4) with manifestations comparable to the 1711 event. Lahar and pyroclastic flows have destroyed villages, destroying all the coconut trees along the coast. **963** inhabitants were killed, particularly in the village of Tabuhan, Khendar and Kolengan (Tanguy et al., 1998; Data Dasar, Gunung Api, 2011).
1856 (Mar. 2-7)	Large phreatomagmatic eruption (VEI 3) with associated pyroclastic and lahar flow that killed 2806 inhabitants. The eruption has also triggered a tsunami event (Wichmann, A., 1893; Siebert et al., 2010, Tanguy et al., 1998).
1875 (Aug.)	Phreatic eruption (VEI 2) with no further report (Siebert et al., 2010; Data Dasar, Gunung Api, 2011).
1883 (Aug. 25-26)	Eruption (VEI 2) but no further detail (Siebert et al., 2010).
1885 (Aug. 18)	Phreatic eruption (VEI 2) but no further detail (Siebert et al., 2010; Data Dasar, Gunung Api, 2011).
1892 (Jun. 7-12)	Large phreatomagmatic eruption (VEI 3). Beginning at 6:10 am – then a huge column was seen ascending into the atmosphere in the afternoon, accompanied by lightning and thunderstorms. Muddy rain turned into pumice and heavy ashfall when the eruption reached the climax of its violence at 9 pm with pyroclastic flow and lahar before it started to fade after midnight. A large number of huts collapsed under the weight of ash and extensive mudflow occurred during and following the event. The eruption has also triggered a tsunami event. 1532 inhabitants were

	reported killed, mainly by pyroclastic and lahar events in many areas, including Mala, Akembuala, Anggis, Mitung, Kolengan, Metih, Khendar and Trijang. Many victims are killed while in church buildings (Wichmann, A., 1893; Van Padang, 1983; Data Dasar, Gunung Api, 2011; Tanguy et al., 1998).
1893	Phreatic eruption (VEI 2) but no further detail (Data Dasar, Gunung Api, 2011; Siebert et al., 2010).
1913 (Mar. 14)	Phreatic eruption (VEI 2) (Data Dasar, Gunung Api, 2011; Siebert et al., 2010).
1921 (Feb.)	Pheatic eruption (VEI 0) – crater lake activity (Data Dasar, Gunung Api, 2011; Siebert et al., 2010).
1922 (Jun.-Sep.)	Pheatic eruption (VEI 0) - crater lake activity (Data Dasar, Gunung Api, 2011; Siebert et al., 2010).
1931 (Apr.-Dec.)	Lava dome started to form in the crater lake in April and then progressively grew until reaching 80 m above the water in Dec. (Data Dasar, Gunung Api, 2011).
1966 (Aug. 12)	At 8:20 (Aug.12), a VEI 4 began with a sudden thick smoke that rose from the crater associated with a strong blast. An hour later another strong blast occurred propelling voluminous amount of ash that subsequently blanketed the summit. Other strong explosions followed until around 13:30 and pyroclastic flow extended 5 km from the crater. Lahars have traveled 7 km toward the coast. along the water channels. Both phenomena have destroyed everything in their respective passages. Kendhar and Mala were the most affected area with 13 and 18 casualties respectively. Eight other inhabitants were also killed in other areas, including 2 officials. In total, the eruption killed 39 and caused the displacement of 11000 inhabitants (Data Dasar, Gunung Api, 2011; Siebert et al., 2010).
1992 (May-Oct. 12)	Phreatic eruption (VEI 1). Before the eruption, the lake volume decreased by 95% from the initial 3.5×10^6 m^3 of water. On Oct. 12, a phreatic eruption occurred (Data Dasar, Gunung Api, 2011; Siebert et al., 2010).
2004 (Jun. 8-10)	Magmatic eruption (VEI 2) building a column of 1000-3000 meters above the crater. The resulting ashfall extended kilometers from the volcano. At Tabukan, 15 km southeast of the volcano the ash was 0.5-1 mm thick. 18648 people were displaced but no one was killed (Data Dasar, Gunung Api, 2011; Siebert et al., 2010).

Table 2. Major and trace composition of Awu lava dome.

	S1 (lava dome)	S2 (lava dome)	S3* (volc. rock)	S4* (south Sangihe Is.)	S5**	S5**
SiO_2 (wt%)	53.95	54.10	52.27	58.50	55.11	54.54
TiO_2	0.77	0.71	0.72	0.61	0.69	0.73
Al_2O_3	18.40	18.90	18.44	18.26	18.73	18.68
Fe_2O_3	8.85	8.60	8.20	7.47	8.53	8.52
MnO	0.21	0.20	0.19	0.16	0.19	0.19
MgO	3.79	3.61	3.44	2.61	3.34	3.42
CaO	8.73	8.85	8.42	7.16	7.76	8.60
Na_2O	3.70	3.53	3.91	3.51	3.52	3.51
K_2O	1.17	1.13	1.21	1.50	1.40	1.21
P_2O_5	0.19	0.16	0.19	0.22	0.22	0.19
LOI	0.30	0.0	0.34	0.94		
Total	99.75	99.83	98.69	100.65	99.49	99.59
Ba (ppm)	227	230	228	214	272	226
Sr	378	378	373	431	419	366
Rb		19	20	30	25.5	19.80
Cs			1.0	0.7	1.00	1.01
Y		23.3	26	51	18.8	20.5
Zr		70.7	74	107	72.8	72.0
Ni		5.4	<5	<5		
Sc		22.4				
V		242.5				
Cr		4.9				
Co		19.4				
Nb		2.6			3.04	2.17
La		4.9			7.25	5.95
Ce		13.8			16.4	14.80
Nd		8.7			10.8	10.30
Sm		2.3			2.90	2.95
Eu		0.72			0.97	1.01
Gd		2.7			3.20	3.45
Dy		2.8			3.43	3.80
Er		1.7			2.20	2.5
Yb		1.92			2.20	2.48
Th		0.4			1.33	1.10

* data from Morrice et al. (1983); ** data from Hanyu et al. (2012).

Table 3. Thermal radiant flux from Awu crater

		IR1	IR2	IR3	Dome
Surface (m2)		92681	1852	1631	13225
Temp. range	**Corrected mean temp. (°)**	**Surface occupied per temperature range (%)**			
16-20 °C*	93.4	51.8	54.2	51.3	78
21-25 °C	97.3	1.1	27.9	13.9	0.5
26-30 °C	101.2	0.4	11.4	13.5	0.1
31-35 °C	105.3	0.3	6.5	14.3	0
36-41 °C	109.8	0.1	0	2.9	0
Mean Radiant flux (MW)		**27 ± 12**	**0.5 ± 0.2**	**0.9 ± 0.3**	**5.6 ± 2.4**

** Note that below 16°C, it was difficult to discriminate the heated zones from the background surface.*

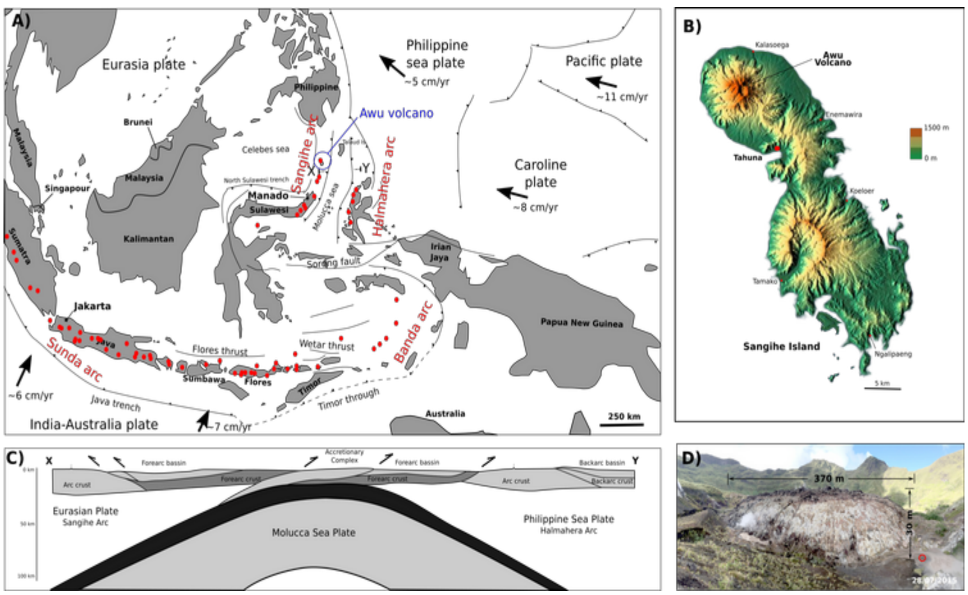

Figure 1. Awu volcano is the northernmost active volcano of the Sangihe arc (A). It occupies the northern portion of Sangihe island (B). 3D map from https://maps-for-free.com. Sangihe and Halmahera arcs constitute the present-day example of arc-to-arc collision (C). The Molucca Sea Plate that existed between the two arc is now sinking deeper beneath the Molucca Sea. Awu's crater is currently occupied by a lava dome (D). Note the person circled in red for scale.

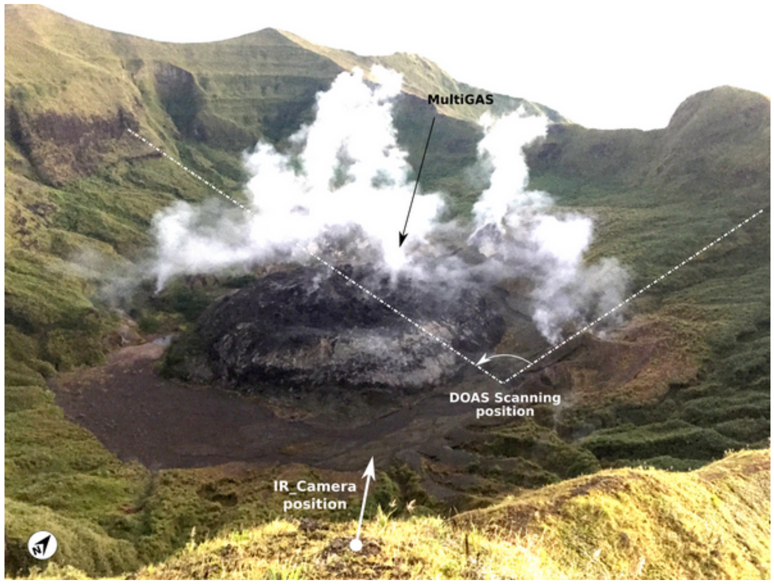

Figure 2. Awa lava dome in the crater. Degassing occurs from the lower crater wall and the northern part of the crater is the main degassing zone. The positions of DOAS scanning, MultiGAS (MG) and Infrared Camera are highlighted. The arrow of the IR_cam denotes the direction of the thermal camera.

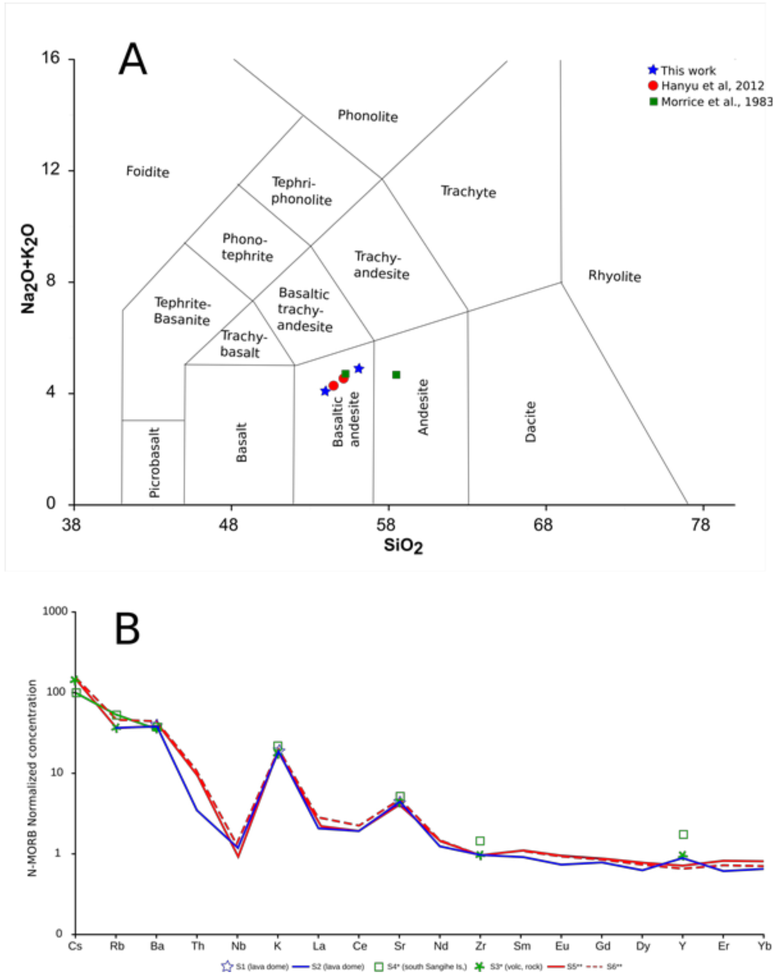

Figure 3. (A) Awu melt source is of basaltic andesite composition. Note that the sample from the southern part of Sangihe island (Morrice et al., 1983) rather indicates an andesite source. (B) Trace elements normalized to N-MORB indicate elevated ratios of LILE, LREE HFSE.

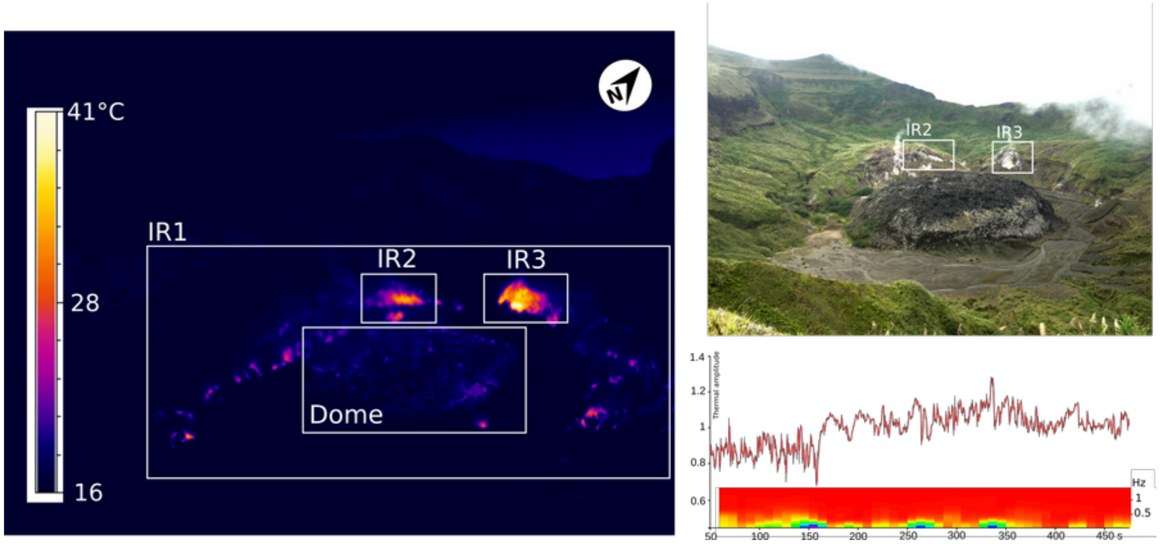

Figure 4. Thermal image highlighting the two most heated surfaces in the crater, as well as the lava dome being less hotter than the surrounding surface. White rectangles (IR1, IR2, IR3 and Dome) are the zones of interest in the radiant flux calculation (Table 3). The picture on the right gives a global view of the dome and its surroundings. The continuous thermal recording highlights a degassing dynamic through the IR3 zone characterized by a thermal fluctuation amplitude of 0.1-0.3 MW and at 0.3-0.4 Hz.

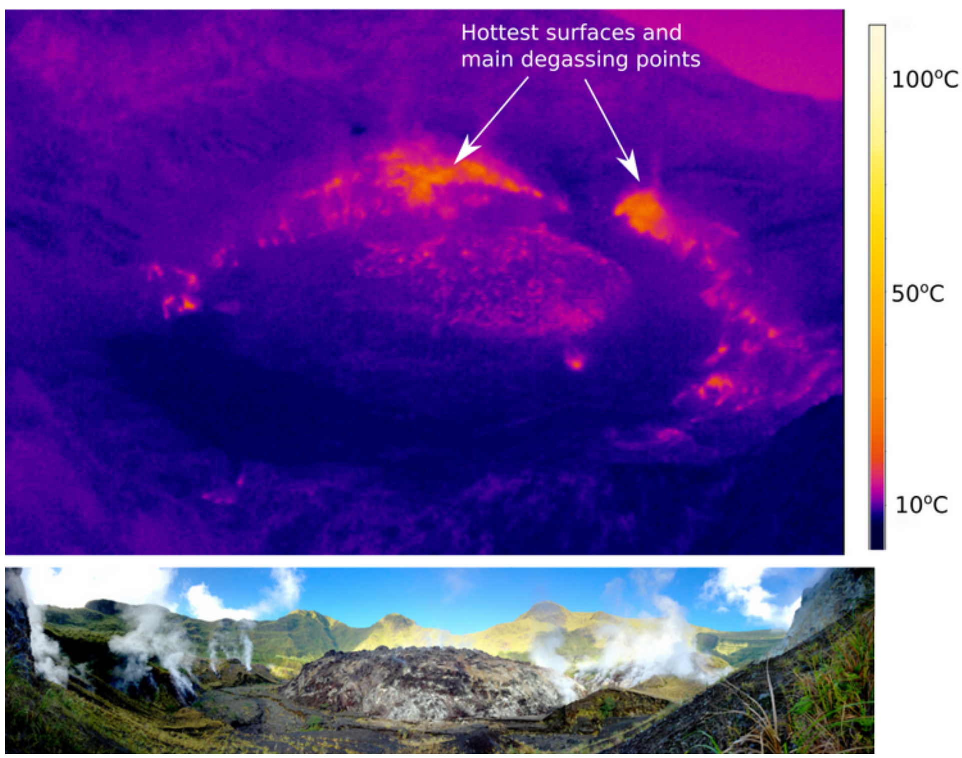

Figure 5. The lava dome and the conduit plug force the degassing to the crater wall. The hot surfaces (photo above) also correspond to the degassing points (picture below).

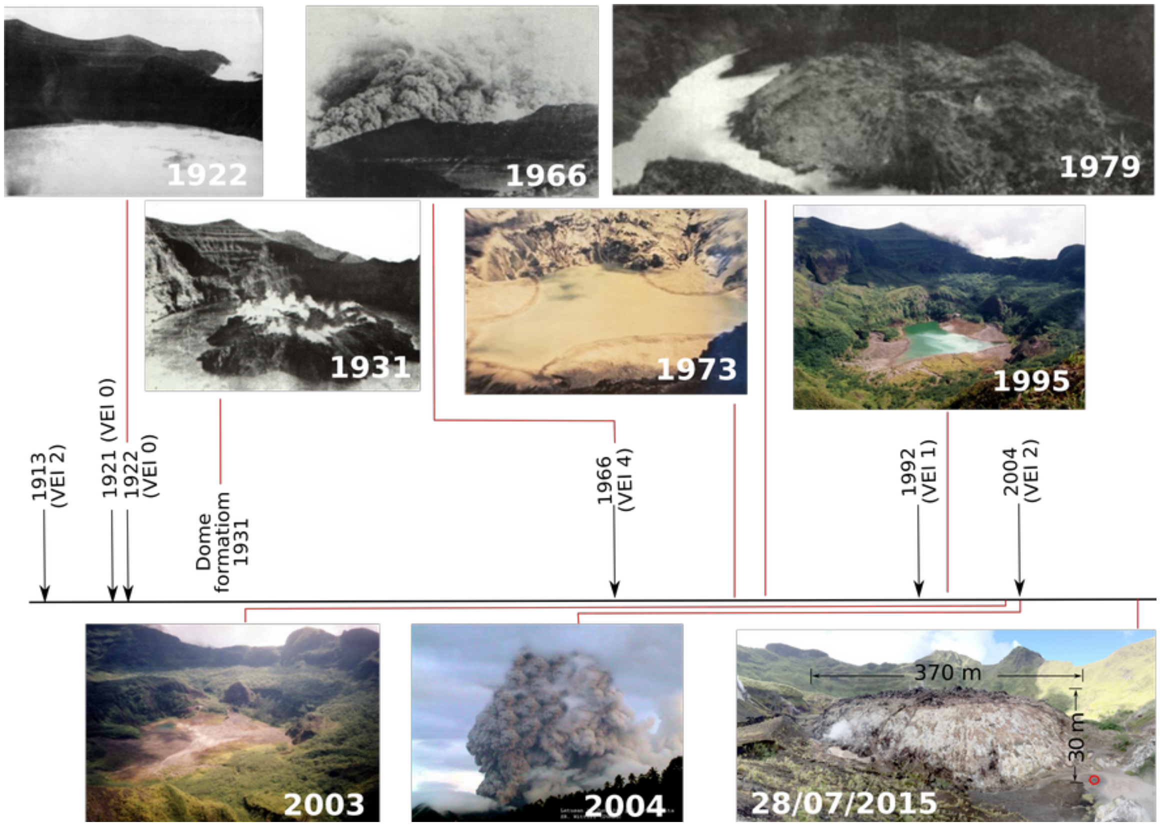

Figure 6. The configuration in Awu's crater is subjected to evolve from crater lake to lava dome emplacement and also from unoccupied crater to coexistence of lava dome and crater lake. Pictures from GVP, 2013 (Awu) except the 2015 (this work).

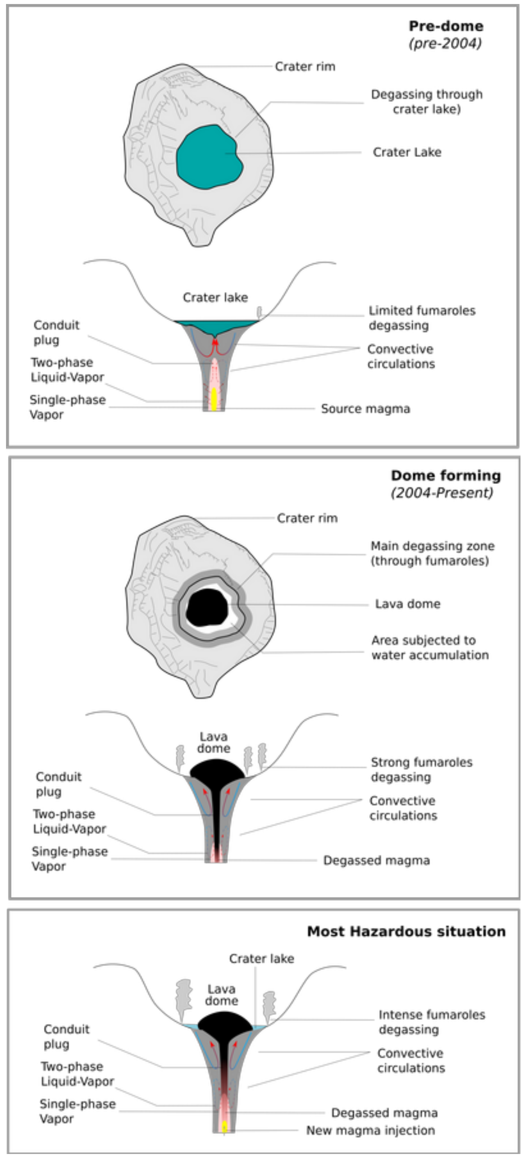

Figure 7. Pre-dome situation: A crater lake in Awu's crater. Few fumaroles on the crater wall. Dome forming situation: Lava dome emerged at the surface leading to lake water dry-out. Numerous fumaroles around the lava dome due to conduit plug. Most Hazardous situation: The cooled lava dome allowed the formation of a new crater lake. The new magma injection may enhance the opening of the conduit plug, leading to subsequent explosive water-magma interaction.