The little known Awu volcano is among the highest CO_2 degassing source on earth

Philipson Bani[1], Etienne Le Glas[1], Kristianto[2], Alessandro Aiuppa[3], Devy Kamil Syahbana[2]

1- Laboratoire Magmas et Volcans, Université Blaise Pascal - CNRS -IRD, OPGC, Aubière, France.
2- Center for Volcanology and Geological Hazard Mitigation (CVGHM), Jl. Diponegoro No. 57, Bandung, Indonesia.
3- Dipartimento DiSTeM, Università di Palermo, Palermo, Italy.

* Correspondence to philipson.bani@ird.fr

Key Points:

- Recent estimates of global volcanic CO_2 output indicate an emission budget of 71- 87 Tg/yr
- The degassing from many remote and isolated volcanoes in Indonesia are yet to be measured
- Ignored in the past, the high CO_2 contribution from Awu volcano (0.9 Tg/yr) needs to be considered in the global emission budget.

Abstract

Awu is one of the remote and little known active volcanoes of Indonesia. It is the northernmost active volcano of Sangihe arc with 18 eruptions in less than 4 centuries, causing a cumulative death toll of 11048. Two of these eruptions were classified as VEI 4. Since 2004, a lava dome occupies the center of Awu crater, channeling the fumarolic gas output along the crater wall. A combined DOAS and MultiGAS measurements highlight a relatively small SO_2 degassing (13 t/d) into the atmosphere. In contrast the measurements spotlight an elevated and non-negligible CO_2 emission into the atmosphere of 2600 t/d, representing 1% of the global CO_2 emission budget from volcanoes. The cause for this high CO_2 degassing may reside in the peculiar geodynamic context of the region, where the slowing down of arc-to-arc collision has enhanced heating of the slab, leading to greater production of fluid rich in carbon.

Plain Language Summary

In the current context of climate change, there is a strong need to better constrain the volcanic volatile contributions into the atmosphere and particularly the CO_2 with respect to the global warming. Despite the effort undertaken over the last ten years by the scientific community, much is still needed to better constrain the global CO_2 emission from volcanoes into the atmosphere. Ongoing efforts are thus focusing on remote and less accessible volcanoes, like those in Indonesia. This work highlights the high CO_2 degassing from the little known Awu volcano, northeast Indonesia. The source of this elevated CO_2 possibly arises from unusual slab carbon delivery into the mantle beneath the volcano.

1/ Introduction

Awu is an active volcano located on Sangihe arc, northeast of Indonesia (Fig.1). It is a large edifice that culminates at 1318 m above sea level with a summit crater of 1500 m in diameter. Since 2004, a lava dome has occupied the central part of the crater. Due to its remote location, little is known about its activity – a paradox since this northernmost volcano of Sangihe arc has undergone through two VEI 4 and three VEI 3 eruptions since it first activity recording in 1640 (Table 1). In total, there are at least 18 eruptions recorded in less than four centuries, thus about one eruption every 20 years. The latest eruption was a VEI 2 in 2004. In the database of volcanic eruption victims compiled by Tanguy et al. (1998), Awu eruptions claimed a total of 5301 victims, mainly following lahar events, including 963 casualties during the 1812 eruption, 2806 during the 1856 eruption and 1532 during the 1892 eruption. But this latter database did not take into account the 2508 victims of the 1711 eruption (Van Padan, 1983; Data Dasar Gunung Api, 2011) and the 3200 inhabitants killed by lahar events following the

1822 eruption (Lagmay et al., 2007). In 1966, the VEI 4 eruption claimed 39 victims, injured 2000 and forced the evacuation of 420,000 inhabitants (Witham, 2005). In total, since 1711, Awu recurrent eruptive activities caused a cumulative number of 11048 fatalities. This figure classifies Awu as one of the most deadliest, yet poorly studied, volcanoes. In this work, we report on the first volcanic gas emission budget for Awu volcano, with an emphasis on its strong CO_2 output.

3/ Methodology

To evaluate the gas composition on Awu volcano, a compact and portable Multi-GAS system built at Università di Palermo (as used by Aiuppa et al., 2015; Bani et al., 2017; 2018) was deployed on July 2015. The instrument was positioned on 3 most activelely degassing points in the crater (Fig.2) and simultaneously acquired at 0.5 Hz concentrations of H_2O, CO_2, SO_2, H_2S, and H_2 in the fumarole's atmospheric plumes. CO_2 was detected by non-dispersive infrared spectroscopy (GasCard NGII; 0–3,000 ppm range) whilst relative humidity (Galltec sensor) was used to calculate H_2O following Buck (1981):

$$H_2O = 6.1121*(1.0007+3.46*P^{-6})*\exp((17.502*T)/240.97+T)*Rh*10^{4}*P^{-1})$$

where P is the pressure, T the temperature and Rh relative humidity. SO_2, H_2S, and H_2 were detected via specific electrochemical sensors (respectively, models 3ST/F, EZ3H, and EZT3HYT "Easy Cal", all from City Technology with calibration range of 0–200 ppm). Data were processed using Ratiocalc (Tamburello, 2015).

In order to derive a degassing output estimate, we performed DOAS measurements in a fixed scanning mode in the crater (Fig.2). To improve chances of catching each degassing source, measurements were performed with an angle of 45° from horizontal, which enable a scanning line just above the crater rim. Twenty four distinct scans were carried out from 8:30 am to 10:40 am (local time) and 23-24 spectra were collected during each scan. The spectrometer used was an Ocean Optics USB2000+ with a spectral range of 290–440 nm and a spectral resolution of 0.5 FWHM. The SO_2 column amounts (ppm m) were retrieved using DOAS calibration and standard analysis procedures (Platt and Stutz, 2008). Reference spectra included in the non-linear fit were obtained by convolving high resolution SO_2 (Bogumil et al., 2003) and O3 (Voigt et al., 2001) cross-sections with the instrument line shape. A Fraunhofer reference spectrum and ring spectrum, calculated in DOASIS, were also included in the fit. The total column amount of the plume cross section was then multiplied by the mean plume rise speed (estimated at 1.3 m/s using thermal camera) to derive the SO_2 emission rate.

4/ Results

Out of 24 scans carried out within 2h of DOAS recording, only 8 scans, acquired on the first part of the measurements, are considered representative (Table 2). They were acquired in clear sky conditions, whilst the other 2/3 of the scans were strongly affected by the rapid formation of cloud coverage. Based on the 8 assumed representative scans, a mean daily SO_2 emission rate of 13±6 tons was obtained, suggesting a rather small degassing, in coherence with the calm volcanic activity state observed in July 2015 (this work).

Multi-GAS recordings highlight distinct gas composition for the 3 measured degassing points (Fig.3, Table 3) with H_2S/SO_2 ratios of 230, 163 and 49, CO_2/SO_2 ratios of 1824, 600 and 297, H_2/SO_2 ratios of 6, 0.8 and 0.1 respectively for MG_Pt1, MG_Pt2 and MG_Pt3 (see Fig.2 for corresponding locations). The water:to:sulfur ratio (H_2O/SO_2 of 1596) was only retrieved at the MG_Pt3 sampling point, where the H_2O concentrations were higher (up to > 6000 ppmv) and correlated with SO_2. In contrast, at MG_Pt1 and MG_Pt2, the H_2O concentrations were lower (of about 1000 ppmv on average) and poorly correlated with other gases. The degassing spot MG_Pt3 exhibited the lowest H_2S/SO_2 (49) and CO_2/SO_2 (297) ratios, and because of its more SO_2-rich signature and more vigorous

degassing, is considered as the most representative of the magmatic system (e.g., with more limited hydrothermal contributions that in H_2S- and H_2-richer MG_Pt1 and MG_Pt2). The gas composition at MG_Pt3 corresponds to 82 mol. % H_2O, 15 mol. % CO_2, 2 mol. % H_2S, 0.05 mol. % SO_2 and 0.02 mol. % H_2 (Table 3), assuming no other representative gas is present in the plume. When used in tandem with the DOAS-derived SO_2 flux, the MG_Pt3 gas ratios imply H_2O, CO_2, H_2S, and H_2 emission rates of 5800 t/d, 2600 t/d, 340 t/d and 0.1 t/d, respectively.

4/ Discussion

Prior to our study here, only one published volcanic gas composition report existed for Awu (Clor et al., 2005). These authors reported on the collection (in 2001) of two close-to-boiling-temperature (96.6 °C) fumaroles in the crater, both exhibiting very hydrous (99.7 mol. %) and CO_2-poor (0.18 mol. %) compositions. The gases collected by Clor et al., (2005) were also manifestly S-poor (<0.003 mol. %), and thus radically different from our recalculated MG_Pt3 gas composition (15 mol.% CO_2, and 2.05 mol. % total S, S_T). Conditions at the time of Clor et al., (2005) sampling in 2001 were very different than in 2015 (this study), as no lava dome existed at that time and the crater area was occupied by a crater lake. Interaction with crater lake water in Clor et al., (2005) is implicated by the more hydrous and S-depleted composition of the gases (water soluble S species are rapidly dissolved during gas transit through volcanic lakes; Christenson et al., 2015). In 2015 instead, no lake was observed and degassing occurred within, and at the margins of, the 2004 lava dome, similarly to what observed at Rokatenda (Primulyana et al., 2017), Lascar (Matthews et al., 1997) or Soufriere Hills (Sparks, 2003).

Our study also provide the first assessment of the volcanic gas output from Awu volcano. The combined DOAS and Multi-GAS results (Table 3) implicate daily mean fluxes of 13 t/d, 5800 t/d, 2600 t/d, 340 t/d and 0.1 t/d for SO_2, H_2O, CO_2, H_2S and H_2 respectively. We caution that since the composition of the SO_2-richest (MG_Pt3) fumarole was used in the calculation, our estimated fluxes above should be viewed as lower ranges for CO_2, H_2S and H_2, as these species are comparatively more abundant (than in MG_Pt3) in the more weakly degassing (but numerous) fumaroles around the Awu dome (exemplified by MG_Pt1 and MG_Pt2, see Fig. 2).

If put in the context of the recent global volcanic SO_2 inventory of Carn et al. (2017), Awu's SO_2 flux contribution into the atmosphere falls below the lower end (32 t/d) of the distribution of the time-averaged SO_2 emissions from the 91 top degassing volcanoes in 2005-2015. Thus, in its current activity level, Awu only contributes ~0.02% of the daily global volcanic SO_2 emission budget of ~63 kt (Carn et al., 2017). In contrast, Awu's CO_2 emissions are significantly high, and rank the volcano in the upper (>90 % percentile sub-category) range of the global volcanic CO_2 flux population (Werner et al., 2019, Fischer et al., 2019). The CO_2 emissions from Awu thus rival those from some of the most strongly degassing volcanoes worldwide (Aiuppa et al., 2019). Assuming the 2015 degassing conditions were representative of the volcano's time-averaged behavior, then with its 0.9 Tg annual CO_2 release Awu would ranks among the top ten strongest volcanic CO_2 sources on earth, contributing to 1-1.3 % of the global CO_2 annual emission from volcanoes (71-87 Tg/yr; Fischer et al., 2019; Werner et al., 2019).

These high CO_2 flux emissions are (at least partially) a direct consequence of the CO_2-rich Awu gas composition (~15 mol. %, and CO_2/SO_2 ratios of 287, in the strongest fumarole MG_Pt3). These CO_2-rich compositions suggest hydrothermal control on degassing even in the most "magmatic" (SO_2-richest) MG_Pt3 fumarole, as supported by the prevalence of H_2S over SO_2 (H_2S/SO_2 ratio of 49, Table 3). 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, below the ~450 °C threshold temperature (Aiuppa et al., 2017) above which hydrothermal S scrubbing (Symonds et al., 2001) becomes negligible. At the <450 °C conditions prevailing at Awu, in contrast, a non-

negligible fraction of the original magmatic SO_2 can be consumed by S-depleting hydrothermal reactions such as (Holland, 1965):

$$4SO_2+4H_2O \rightarrow H_2S + 3H_2SO_4$$
$$3SO_2+2H_2O \rightarrow S+2H_2SO_4$$

These reactions, occurring upon magmatic gas ascent and cooling into hydrothermal envelopes (Symonds et al., 2001), lead to discharge of a CO_2-rich and S_T-poor fumarolic gas. For example, the typical CO_2/S_T range of high-temperature magmatic gases in Indonesia is between 0.3 and ~5 (Aiuppa et al., 2015, 2017), with an average at ~4 (Hilton et al., 2002). The CO_2/S_T ratio in the MG_Pt3 Awu fumarole is 5.7, thus implying deposition of a few % up to >90% of the original magmatic SO_2 content.

While thus some extent of hydrothermal processing is implicated by the composition of all Awu fumaroles, including MG_Pt3, we still note that the CO_2/S_T of 5.7 is lower than the threshold value of 10, which is thought to be indicative for magmatic affinity for the gas (Fig. 4; Fischer and Chiodini, 2015). Combining the calculated equilibrium temperature (380°C) with the CO_2/S_T ratio of 5.7 (Fig. 4, inset), the Awu 2015 MG_Pt3 gas falls in the field of mixed magmatic-hydrothermal gases defined by Aiuppa et al. (2017). We conclude, then, that the 2015 Awu gas composition reflects a combination of (i) magmatic gas supply from a magmatic source plus (ii) some variable extent of hydrothermal processing and S deposition prior to surface discharge.

In view of the above, and also given that CO_2 is less sensitive to scrubbing because of its lower aqueous solubility and reactivity (Symonds et al., 2001), we consider it possible that the high CO_2 emissions are hints for the presence of a carbon-rich melt source beneath Awu volcano. A C-rich magmatic source would be consistent with the findings from Jaffe et al. (2004) and Clor et al. (2005) who found high $CO_2/^3He$ ($64–180\cdot10^9$) and $\delta^{13}C$ (≥-2 ‰) values (in addition to a nitrogen isotope signature of -3.3 ‰) at Awu and Karangetang, the two volcanoes at the northern part of the Sangihe arc. Such positive C isotope compositions (and C excesses relative to ^3He) are likely indicators for the involvement of C-rich, slab sediment-derived fluids in the mantle source. The Sangihe forearc is currently overriding the Halmahera forearc (Hall and Wilson, 2000; Jaffe et al., 2004; Bani et al., 2018) (Fig.1) and the collision event is more advanced in the northern Molucca sea (Morris et al., 1983) where slow-down of collision has been evidenced from seismic recording (McCaffrey, 1983; Pubellier et al., 1991). Such scenario may possibly lead to enhanced heating of the slab (Peacock et al., 1994), thereby promoting greater production of C-rich melts and/or fluids beneath Awu volcano (Jaffe et al., 2004). The hypothesis of a C-rich magmatic source will require testing from analysis of volatiles stored in crystal-hosted melt inclusions and, if verified, may imply sizeable CO_2 emissions during the relatively frequent explosive (up to VEI 4) Awu eruptions (Kodera et al., 2008).

5/ Conclusion

Awu is the largest and northernmost active volcano of Sangihe arc. Due to its remote location very little is known about its activity, a paradox since this volcano went through numerous eruptive activities, including two with VEI 4. Since 1711 these recurrent eruptions claimed 11048 fatalities, a figure that emphasizes Awu as one of the deadliest volcanoes worldwide. In July 2015, a gas survey carried out in the crater spotlights an elevated CO_2 degassing from the numerous fumaroles around a lava dome situated in the center of the crater. Despite a low SO_2 flux of 13 t/d, the CO_2 emissions are relatively high, with an estimated annual output of 0.9±0.4 Tg/yr that represent ~ 1% of the global volcanic CO_2 emission budget. This high CO_2 output may result from the peculiar geodynamic context of the region, where the slow down of arc-to-arc collusion has produced heating of the slab, potentially leading to larger delivery of C-rich fluids/melts.

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Tables and Captions

Table 1. History of Awu eruptive activity. Most of the information is 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 causalities 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 $3.5x10^6$ 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. SO_2 flux obtained from two hours scanning DOAS.

	Start time (LT)	Scan step (m)	Nber of spectra	Mean CA (mg/m2)	SO_2 flux	
					kg/s	t/d
Scan 1	*08:38*	*15*	*33*	*62*	*0.04*	*4*
Scan 2	08:44	47	24	74	0.11	9 ± 4
Scan 3	08:52	47	24	189	0.27	23 ± 10
Scan 4	09:00	47	24	80	0.11	10 ± 4
Scan 5	09:08	47	24	89	0.13	11 ± 5
Scan 6	*09:12*	*47*	*24*	*48*	*0.05*	*6*
Scan 7	09:16	47	24	96	0.14	12 ± 5
Scan 8	09:19	47	24	118	0.17	15 ± 7
Scan 9	09:25	47	24	102	0.15	13 ± 6

Scan 10	09:33	47	24	104	0.15	13 ± 5
Scan 11	*09:41*	*47*	*24*	*24*	*0.03*	*3*
Scan 12	*09:53*	*47*	*9*	*170*	*0.03*	*3*
Scan 13	*09:59*	*15*	*23*	*23*	*0.01*	*1*
Scan 14	*10:02*	*15*	*23*	*30*	*0.01*	*1*
Scan 15	*10:05*	*15*	*23*	*63*	*0.03*	*2*
Scan 16	*10:07*	*15*	*23*	*48*	*0.02*	*2*
Scan 17	*10:10*	*15*	*23*	*46*	*0.02*	*2*
Scan 18	*10:14*	*15*	*23*	*54*	*0.02*	*2*
Scan 19	*10:18*	*15*	*23*	*88*	*0.05*	*4*
Scan 20	*10:23*	*15*	*23*	*58*	*0.03*	*3*
Scan 21	*10:24*	*15*	*23*	*52*	*0.03*	*3*
Scan 22	*10:27*	*15*	*23*	*64*	*0.04*	*3*
Scan 23	*10:30*	*15*	*23*	*66*	*0.04*	*3*
Scan 24	*10:33*	*15*	*23*	*53*	*0.03*	*2*
Mean SO_2 emission rate: 13 ± 6 t/day						

Notes: Only scan 2, 3, 4, 5, 7, 8, 9, 10 are considered in the mean emission rate. Other scans (grey background) are underestimating the emission due to initialization of the scanning system (scan 1, 6) and the rapid cloud build up (scan 11-24).

Table 3. Gas composition, gas ratios and gas fluxes obtained from a combined Multi-GAS and DOAS recordings. Gas composition and flux are calculated from MG_Pt3 considered as more representative of the system.

	MG_Pt1	**MG_Pt2**	**MG_Pt3**
H_2S/SO_2	230 ± 110	163 ± 62	49 ± 20
CO_2/SO_2	1824 ± 850	600 ± 230	287 ± 164
H_2/SO_2	6 ± 4	0.8 ± 0.1	0.3 ± 0.1
H_2O/SO_2	-	-	1596 ± 670
	Composition (mol %)		Flux (t/d)
SO_2	0.05 ± 0.02		13 ± 6
H_2O	82.5 ± 34.1		5800 ± 2400
CO_2	14.8 ± 6.8		2600 ± 1200
H_2S	2.5 ± 1.1		340 ± 150
H_2	0.02 ± 0.01		0.1 ± 0.04

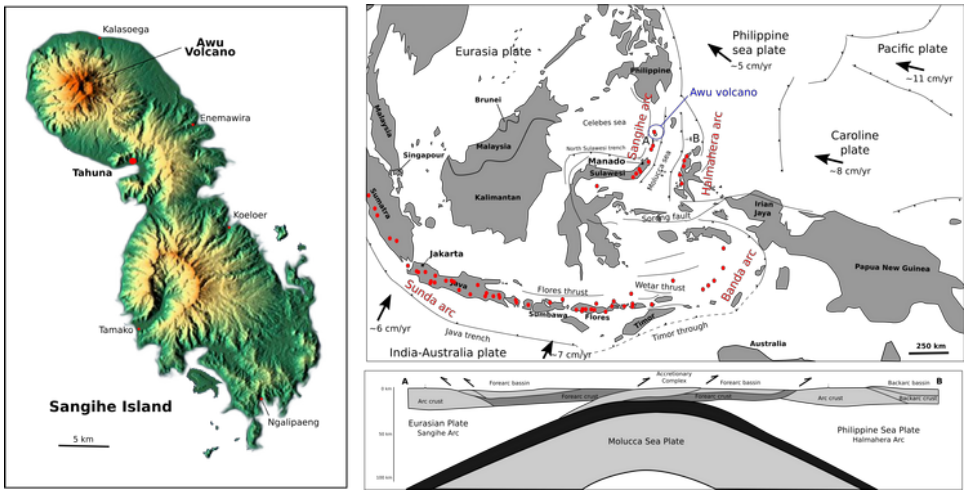

Figure 1. Awu volcano occupying the northern portion of Sangihe island (3D map from https://maps-for-free.com) (left). A sketch highlighting the main players behind the tectonic setting of Indonesia (right). The main plates and their motions are positioned, as well as the volcanic arcs. Awu volcano circled in blue is located on Sangihe arc that faces the Halmera arc to the east. The red dots denotes active volcanoes. The A-B cross section (schema below) highlights the collision of Sangihe and Halmahera arcs (adapted from Jaffe et al., 2004).

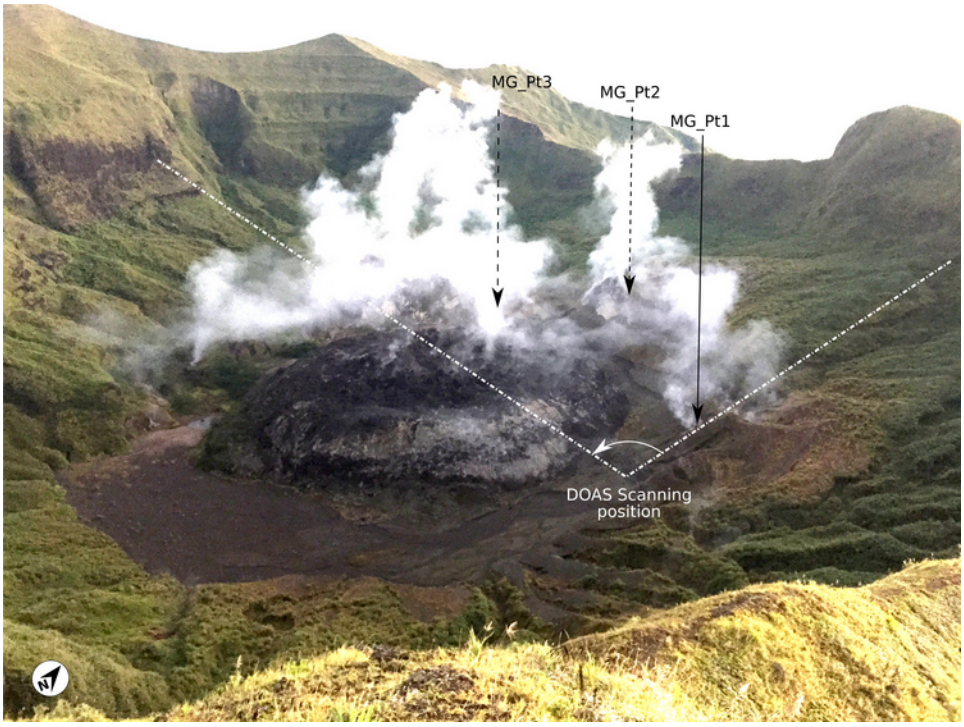

Figure 2. Awu lava dome in the crater. Degassing occurs from the lower crater wall and mainly to the northern part of the crater. The positions of DOAS scanning and MultiGAS (MG) are provided.

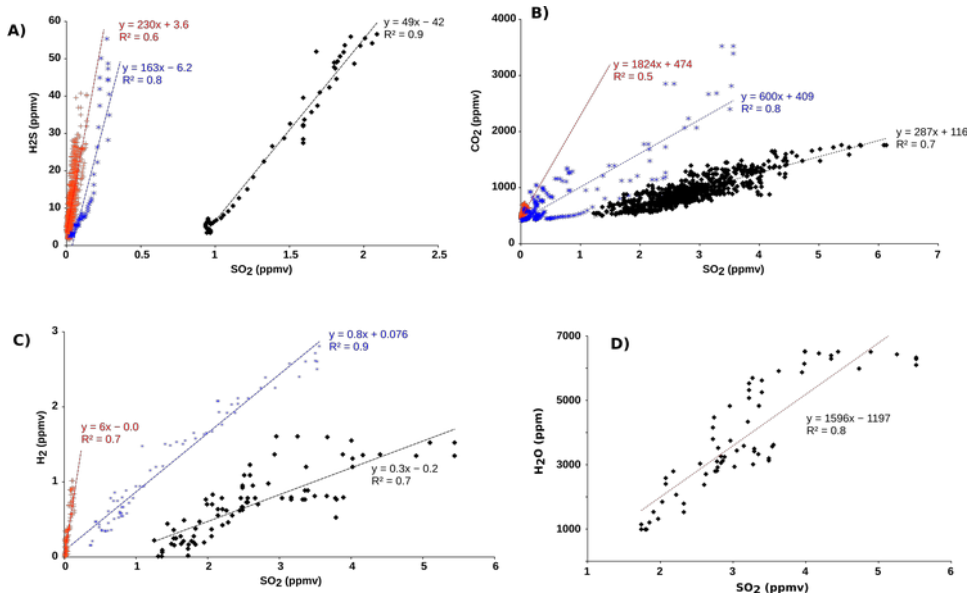

Figure 3. Gas composition obtained from 3 different locations in the crater, including MG_Pt1 (red), MG_Pt2 (blue) and MG_Pt3 (black). The changes of gas compositions between sampling points are highlighted by the gas correlation to SO_2, including H_2S (A), CO_2 (B), H_2 (C) and H_2O (D) (see Fig.2 for measurement locations). For H_2O/SO_2 a correlation was only found at point MG_Pt3.

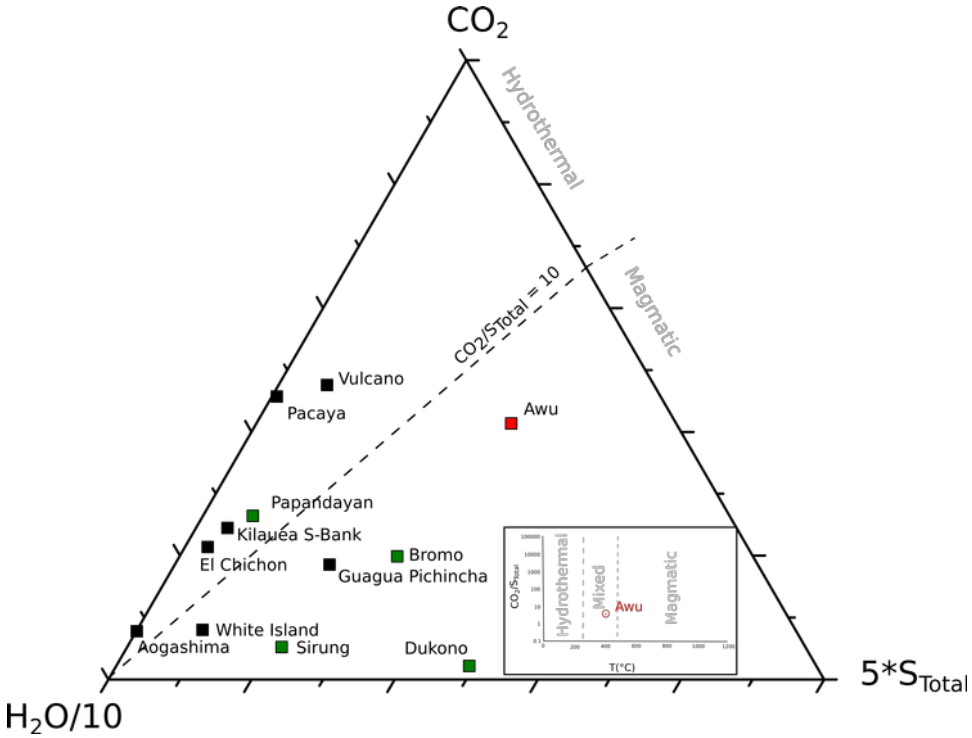

Figure 4. Triangular diagram showing the relative proportions of H_2O, CO_2, and S_T (S_T being SO_2 + H_2S) on Awu in comparison to hydrothermal gases from other volcanoes in Fischer and Chiodini (2015) and to other volcanoes in Indonesia (green), including Sirung (Bani et al., 2017), Bromo (Aiuppa et al., 2015) and Dukono (Bani et al., 2018). Awu is also plotted in the mixed zone according to the CO_2/S_T and gas temperature following Aiuppa et al. (2017).