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First gas and thermal measurements at the frequently erupting Gamalama volcano (Indonesia) reveal a hydrothermally dominated magmatic system

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Highlights

- Gamalama a frequently erupting volcano but poorly studied
- A volcanic system dominated by hydrothermal manifestation
- A remarkable shift of volcanic activity from the crater center to the peripheral fractures zones
- Fractures have weakened the hydrothermal seal leading to recurrent phreatic eruptions

Abstract

The first gas and thermal measurements at the summit of the Gamalama volcano indicate that the system is dominated by hydrothermal processes. This is highlighted by the prevalence of H₂S over SO₂ (H₂S/SO₂ = 2-8), a high CO₂/SO₂ ratio (76-201), and a low heat transfer (3.0 MW) to the surface. A relative variation in gas composition is observed along the degassing fracture zone, possibly due to partial S scrubbing. Despite this surface hydrothermal signature, the system exhibits high gas equilibrium temperatures (425-480°C), indicating that fluids are not exclusively derived from a boiling hydrothermal aquifer, but also sourced by cooling and crystallizing basaltic magma at deep that continues to inject magmatic fluids into the system. This hydrothermally dominated activity on Gamalama possibly persisted over the last two decades, during which a high number of eruptive events were witnessed. The period coincides with the opening of large fractures at the summit that subsequently shifted the volcanic activity from the crater center to the peripheral fractures zones. These fractures that possibly developed in response to the regional geodynamics, have weakened the hydrothermal seal, allowing the pressure developed by the hydrothermal-magmatic system and promoted by the high annual rainfall, to rapidly exceeds the tensile strength of the seal leading to the numerous phreatic eruptions.

Keywords: Gamalama volcano; dominated hydrothermal system; pressure and tensile strength

1. Introduction

Gamalama is a stratovolcano with a near-perfect cone-shape having a subaerial diameter of 12 km. Located off the coast of Halmahera island, this 1715 m high volcano is one of the 5 active volcanoes of the Halmahera arc (Fig.1). Since 1510, Gamalama has experienced 66 confirmed eruptions, producing dense columns of ash and incandescent material, voluminous lava flows, pyroclastic flows as well as lahars (GVP, 2013). The volcano hosts a city of about 200,000 inhabitants on its southeastern flank (Fig.1) – a perfect illustration of a City on Volcano. In 1988, 3500 inhabitants were evacuated out of the island in response to a strong eruptive event. In 1983 and 2011, thousands of inhabitants were displaced from exposed zones to safer areas (GVP, 2013). Due to abundant ash emissions, the Sultan Babullah International airport was regularly forced to close. This was the case on July 18, 2005, on Aug. 3-4, 2017, and on Oct. 4, 2018 (GVP, 2013). About 11% of the eruptive events are classified as moderate-to-large eruptions with VEI 3, whilst 70% are considered as moderate eruptions with VEI 2 (GVP, 2013). A major eruptive event on Gamalama in September 1775, formed the Tolire maar, burying the village of Soela Takomi, and killing 141 inhabitants (Dasar, 2011, Mei et al., 2016). More recently, in 2011, a lahar event claimed 4 deaths (GVP, 2013), thus a total of 145 direct victims are recorded from Gamalama volcanic activities over the last two and a half centuries.

The particularity on Gamalama volcano, according to the Center of Volcanology and Geological Hazard Mitigation (CVGHM), the institution in charge of the volcano monitoring in Indonesia, is its capacity to develop eruptive events with very short precursory signals and only a few volcanic quakes before eruptions (volcano news: www.vsi.esdm.id). Such a character constitutes a huge challenge for Gamalama volcano observatory who is struggling to provide timely warnings to inhabitants. To gain insights into the recent volcanic activity of Gamalama, a field investigation was carried out at the summit on September 21, 2018, during which crater temperature distribution and radiant flux, as well as the chemical composition of the gas plume, were characterized for the first time. Here we present the results of this field investigation.

2. Methodology

Gas composition on Gamalama was measured using a Multi-component Gas Analyser System (Multi-GAS; Aiuppa et al., 2005; Shinohara, 2005). This portable instrument measures the concentrations of CO₂, SO₂, H₂S, H₂, as well as the pressure (P), the temperature (T), and the relative humidity (RH). This latter is converted into plume H₂O concentrations using the formula outlined in Buck (1981):

$$\text{H}_2\text{O} = 6.1121 \cdot (1.0007 + 3.46P^{-6}) \cdot \exp\left(\frac{17.502 \cdot T}{249.97 + T}\right) \cdot \text{RH} \cdot 104 \cdot P^{-1}$$

H₂O is the water vapor content in ppm, P is the pressure in mbar, T is the air temperature in °C

The CO₂ gas is detected by near dispersive infrared spectroscopy (range 0-3,000 ppm) while SO₂, H₂S, H₂ gases were quantified using specific electrochemical sensors models (range 0-200 ppm). Data were processed and analyzed using ratiocalc software (Tamburello, 2015). During field measurements, the Multi-GAS was positioned at 3 different degassing points at the summit of the Gamalama volcano (Fig.3). First,

the instrument was positioned on the rim and recorded a gas that diffused through a fumarolic area of ~500
75 m². Then the multiGAS was moved into the plume released by the upper part of the southwest fracture and
was placed ~40 m from the main degassing point. Finally, the instrument was positioned less than 5 m
above the main degassing point of the southern part of this southwest fracture. The relative humidity of
>80% in the morning, during the first of recording at MG1, has dropped to 30% at MG2 and MG3 at around
mid-day, whilst the air temperature increased from <20°C to 30°C.

80 To characterize temperature distribution and heat flux on the summit of the Gamalama, a PI640 OPTRIS
infrared camera was deployed on the crater rim. This miniature infrared camera 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 640x480 pixels and the operating waveband is 7.5-13 μm. The maximum frame rate is
80 Hz. The radiant flux (Q_{rad} in W) estimation is obtained using the following equation: $Q_{\text{rad}} = A\epsilon\sigma(T_s^4 - T_a^4)$,
85 where A is the hot surface (in m²), ϵ is the emissivity (0.9 for basalt), σ is the Stefan-Boltzmann constant
(5.67×10^{-8} W m⁻² K⁻⁴), T_s and T_a correspond to the hot surface and ambient temperature (in K) respectively.
Thermal results are corrected for oblique viewing angle, following the approach detailed in Harris (2013)
and the temperature values are corrected for atmospheric influence relying on ACPC models
(<https://atmcorr.gsfc.nasa.gov/>) and validated with closer thermal recording. The radiant flux was calculated
90 at 5 different temperature ranges (32-35°C; 36-40°C, 41-45°C, 46-50°C, and >50°C) then summed for the
entire zone of interest (Table 1). The values below 32°C were difficult to discriminate from the background
and therefore considered as background.

95 3. Result

The thermal infrared camera survey on Gamalama indicates that the heat dissipation is relatively
confined to the western part of the crater and extends outside the crater along the southwest fracture zone
(Fig.2), where the maximum temperature of ~125°C is recorded. The heated surface in the main crater is
equivalent to ~4500 m², whilst along the southwest fracture zone, ~310 m² of the surface is heated above
100 the background level (Table 1). The total radiant flux calculated for these heated surfaces is 3.0 MW,
including 2.7 MW of heat through the crater and 0.3 MW through the southwestern fracture zone. However,
this latter value should be considered minimum since the area is the main degassing zone, thus gas may
strongly alter the thermal radiation, as seen on Etna by Sawyer and Burton (2006). From visual
observation, gas released from the crater was negligible, compared to the more consistent degassing
105 through the southwestern fracture zone.

The Multi-GAS measurement results obtained on Gamalama highlight different gas compositions for the
three recording points (Fig.3, Table 2). At MG1, the highest elevation recording position (1698 m), results
indicate a strongly diluted gas with H₂O, CO₂, SO₂, H₂S, and H₂ concentrations of 7000-14000, 450-770,
0.05-0.13, 0.3-0.4, and 2.0-4.0 ppm v respectively. There is no correlation between these gas components,
110 thus no acceptable gas ratio can be obtained at MG1. However, the near absence of SO₂, and H₂S (Fig.3)

that contrasts with the relatively high abundance of CO₂ and H₂ reflects a prevalent gas origin from relatively “cold” crater floor emissions of diffusing gas to the surface. In these diffuse, cold emissions, CO₂ and H₂ are typically more abundant (and can persist to the surface) because of their lower reactivity (compared to S compounds that are easily scavenged by subsurface reactions with rocks and water) (Rye 2005, Ohmoto and Rye 1979; Rye 1993; Giggenbach 1997; Symonds et al., 2001). At the recording point MG2, situated ~20 m below MG1, the H₂O, CO₂, SO₂, H₂S, and H₂ concentrations correspond to 3000-12000, 395-550, 0.2-1.2, 0.4-6.5, and 0.6-4.0 ppm v respectively. There is a notable decrease in H₂O, CO₂, and H₂ concentrations from MG1 to MG2, whilst SO₂ and H₂S show a parallel increase in concentration. The gas is less diluted compared to MG1, thus good correlations are obtained between gas components, giving H₂O/SO₂, CO₂/SO₂, H₂S/SO₂, and H₂/SO₂ ratios of 5895±2979, 201±50, 7.9±0.9, and 1.4±0.9 respectively. At the measurement point MG3, located more than 50 m below MG1, the gas has the lowest concentration of H₂O (1000-7000 ppm v) and the highest SO₂ content (0.3-1.6 ppm v). The CO₂ (360-490 ppm v), H₂S (0.1-0.9 ppm v), and H₂ (0.0-3.5 ppm v) concentrations decrease, compare to MG2. The gas to SO₂ ratios at MG3 (Fig.4) correspond to 3169±1144, 76±12, 2.5±0.3 and, 1.2±1.0 for H₂O/SO₂, CO₂/SO₂, H₂S/SO₂, and H₂/SO₂ respectively. Assuming that this less diluted gas at MG3 is the most representative of the magmatic system, given the highest SO₂ concentrations, then we infer the Gamalama gas as H₂O-rich (97.5% of the plume content), with other gas components represent 2.3%, 0.03%, 0.08% and 0.04% for CO₂, SO₂, H₂S, and H₂ respectively.

4. Discussion

4.1. Combined hydrothermal and magmatic fluids

Our gas measurements indicate a prevalence of H₂S over SO₂ with the H₂S/SO₂ ratio of 2 to 8 (Table 2, Fig.4) suggesting an effective conversion from SO₂ to H₂S at hydrothermal conditions. Oxidizing (SO₂-rich) magmatic gases can be converted into H₂S in the reducing hydrothermal envelope by a variety of gas-gas and gas-liquid reactions, such as (Holland, 1965): $\text{SO}_2 + 4\text{H}_2\text{O} \rightarrow \text{H}_2\text{S} + 3\text{H}_2\text{SO}_4$. Besides, upon its ascent, deeply rising volatiles also interact with hydrothermal rock surfaces, during which SO₂ is reduced by FeO in mineral phases, according to Giggenbach (1987): $\text{SO}_2 + 6(\text{FeO}) + \text{H}_2\text{O} \rightarrow \text{H}_2\text{S} + 6(\text{FeO}_{1.5})$. The efficiency of the rock buffer in converting the SO₂ into H₂S is likely to be a function of the intensity and duration of fluid-rock interactions (Giggenbach, 1987). As such, the high H₂S/SO₂ ratio on Gamalama suggests prolonged fluid-rock interactions, which contrasts with other volcanic systems in Indonesia in which faster rising magmatic fluids through well-defined channels (Gamkonora, Saing et al., 2020) or open vents (Bromo, Aiuppa et al., 2014; Dukono, Bani et al., 2018) have led to low H₂S/SO₂ ratios. A shallow magma or magmatic dyke emplacement can also induce a low H₂S/SO₂ ratio. The high CO₂/SO₂ ratios of 76-201 obtained on Gamalama are also well above the magma value of 6-9 or 4 obtained on Merapi (Fischer, 2008) and Bromo (Aiuppa et al., 2014) respectively. Such high CO₂/SO₂ values are common in hydrothermal systems given the lower sensitivity to magmatic gas scrubbing of CO₂ that results from its lower (relative to SO₂) aqueous solubility and reactivity (Symonds et al., 2001). Gamalama degassing

150 during the period studied in this work is thus dominated by hydrothermal processes. This is additionally supported by the gas compositions measured at of MG2 and MG3 sites when plotted in the CO₂-H₂O-Sr diagram (Fig.5). The gases plot along the H₂O-CO₂ axis, within the area of hydrothermal gas composition, comparable to the Papandayan hydrothermal system (Fischer and Chiodini, 2015). Gas from other Indonesian volcanoes, including Bromo (Aiuppa et al., 2015), Sirung (Bani et al., 2017), Dukono (Bani et al., 2018), and Gamkonora (Saing et al., 2020), all plot at S-rich compositions, typical of the magmatic compositional field. Gas composition at MG3, situated about 35 m below MG2, displays relatively lower ratios of H₂O/SO₂, CO₂/SO₂, H₂S/SO₂, and H₂/SO₂ (Table 2, Fig.4). This relative distinct gas compositions between MG2 and MG3 is possibly due to slower fluid ascent to the surface, and consequently more effective S scrubbing (Symonds et al., 2001) at MG2. In contrast, the periodically strong degassing dynamic visible at MG3, compared to continuous degassing at MG2 (Fig.3), indicates an over-pressured gas discharge system, and possibly a deeper source area that enables relatively faster gas ascent to the surface. Note that this MG3 point is situated towards the end of the southwestern fracture, where the gas flow path to the surface is likely less defined (Fig.3).

This hydrothermal character of Gamalama is coherent with the low heat flux of 3 MW obtained in this work (Table 1) and 5 MW highlighted by MODVOLC on Aug. 4, 2003, outside eruptive periods (<http://modis.higp.hawaii.edu/>). For comparison, these values are far lower than those measured on other volcanoes, including the hydrothermal system of Vulcano Island, where Harris and Maciejewski (2000) obtained 45-67 MW of heat flux. However, during the September 2012 eruption of Gamalama (GVP, 2013), MODVOLC established a heat flux of 44 MW, which thus indicates that thermal energy at the surface of Gamalama is subjected to change with the activity. Indeed Gamalama has experienced strong magmatic activities in the recent past, highlighted by ejections of incandescent juvenile pyroclastic materials in 1980, 1983, 1990, and 1993 (GVP, 2013), and lava flows in 1983 and 2014 (GVP, 2015). DOAS gas measurements carried out during the July 2015 eruption indicate a strong magmatic degassing with a mean SO₂ flux of 1235 t d⁻¹ (Table 3). This figure is much higher than the magmatic degassing at Dukono, consider as the strongest and permanent SO₂ source in Indonesia (820 t SO₂ d⁻¹; Bani et al., 2018). Unfortunately, we did not have a DOAS at disposal for SO₂ flux measurements in 2018. However the degassing, although consistent, produced a relatively small-scale plume, comparable in size to the plume of the nearby Gamkonora volcano (Saing et al., 2020). It is thus likely that the 2018 manifestations on Gamalama, as observed in this work, were possibly sustained by a progressively cooling stored magma.

180 The gas equilibrium temperatures, obtained by resolving together the SO₂/H₂S vs. H₂/H₂O redox equilibria (Giggenbach, 1987; Aiuppa et al., 2011; Moussallam et al., 2017), corresponds to 425-480°C, much higher than the maximum temperature observed with the infrared camera (Fig.2, Table 1). Such high equilibrium temperatures likely reflect quenched equilibrium conditions, reached below the surface as hot fluid ascends through, and interact with, the surrounding rocks. Assuming that the above equilibrium gas temperatures are representative of the system, we then infer that the gas released at Gamalama may not exclusively be derived from boiling hydrothermal aquifers, whose temperatures are generally below 300°C (Giggenbach,

185 1980; Chiodini and Marini, 1998). Instead, we propose that the emitted gas is sourced by combined contributions from a magmatic cooling dike and hydrothermal processes within a cooling edifice. This partial but detectable magmatic gas contribution is supported by the low but detectable SO₂ in the plume that is inconsistent with an exclusive hydrothermal origin. Contrasting the gas temperatures against the CO₂/S_T ratios of 22-23 (where S_T corresponds to SO₂ + H₂S), the Gamalama gas plots in the “mixed” gas
190 field (Fig.5; Aiuppa et al, 2017), confirming a contribution from the magma, similar to Papanayan (Fischer and Chiodini, 2015).

Bulk compositions of the fresh rock sampled in 2018 (this work) and analyzed using ICP AES at the LMV (Laboratoire Magmas et Volcan) indicates that Gamalama is sustained by a basaltic magma (Fig.6). The 1907 lava flow and the ejected material of the 1990 eruption are also issued from a basaltic magma
195 (Mawardi et al., 1991).

4.2. Fractures and phreatic events

On October 4, 2018, 23 days after our field campaign at the summit, Gamalama underwent an eruptive event with no precursory signals (GVP, 2018). Such a sudden and short-lived eruptive events are
200 typical of phreatic eruptions (Stix and de Moor, 2018). The event lasted 3 days and released 30 t d⁻¹ of SO₂ (GVP, 2018), much lower than the 1235 t d⁻¹ of the 2015 eruption (Table 3), in accord with the phreatic nature of the event. Since 1510, Gamalama has experienced two phases of elevated activity, as marked by an increased eruptive frequency (Fig.7). A first increase was reported in the mid-19th-Century but, being concomitant with the establishment of the Dutch colony, it's statistical significance is unclear as it may
205 merely reflect improved observation and reporting (Dasar, 2011). The second phase of heightened activity commenced in 2003, with 9 reported (7 confirmed) eruptions. Six out of the 9 eruptions (in 2007, 2008, 2012, 2014, 2016, 2018) displayed a phreatic signature with low intensity (VEI 1) and short duration (1-7 days) (GVP, 2013), whilst 3 other eruptions (in 2003, 2011 and 2015) were of relatively higher intensity (VEI 2) and lasted between 18 and >60 days (GVP, 2013) suggesting a possible involvement of magma
210 inputs. These hydrothermal and magmatic behavior of Gamalama over the last 17 years contrasted with the systematic magmatic manifestations observed between the first detailed eruptive report in 1980 and 2003 (GVP, 2003). Note however that there is no detailed study on the recent eruptive products, thus the so-called phreatic events could as well be phreatomagmatic (Miyagi et al., 2020) but this is yet to be validated. There has been no significant magma source evolution at Gamalama between 1907, 1990, and
215 2018, as highlighted by relatively uniform rock chemistry (Fig.6), which suggests no significant change in magma supply. Degassing of mafic magma at depth may supply the required magmatic volatiles to sustain the surface fumarolic activity and the recurrent eruptions, similar to Aso and Ontake volcanoes (Stix and de Moor, 2018). When magmatic fluid is injected into the hydrothermal system, it condenses and vaporizes the liquid hydrothermal water. Such a process that occurs at high temperatures may induce host rock alteration
220 and formation of sulfur precipitates (Christenson et al., 2010), ultimately leading to the development of a hydrothermal seal (Fig.8, Stix and de Moor, 2018). This latter may play a direct role in driving the

explosivity of phreatic eruptions. When the seal is in place, overpressure can be achieved as driven by the accumulation of ascending mixed hydrothermal-magmatic fluids, finally driving the volcano to erupt in a phreatic or phreatomagmatic event. On Gamalama, this hydrothermal seal has possibly been (at least partially) disrupted by the large fractures, formed at the summit between 2002 and 2011, according to the series of cloud-free satellite pictures available from google earth (Fig.7). Indeed, the summit morphology of Gamalama has evolved from a well circular central crater in 2002 to a fractured crater in its present state. The main active zone has subsequently shifted from the central to the peripheral fracture zones over the same period (Fig.7). This morphology evolution coincides with the increase of eruptive events, supporting the hypothesis of hydrothermal seal disruption. Hence, pressure build-up within the Gamalama hydrothermal system, caused by rising magmatic gases and by infiltrating meteoric water (the annual rainfall is >2000 mm), may rapidly exceed the tensile strength of the weakened, partially disrupted seal, leading to an increased number of phreatic events (Houghton et al., 2015). Periodically, overpressure development in the deep magma storage zone leads to intermittent magmatic eruptions (Stix and de Moor, 2018).

It is still unclear how the summit fractures are formed, however, these are common by-products of volcanic activity (Lanzafame et al., 2003). They are generally made up of extensional fractures and normal faults, associated with dike emplacements (Rubin and Pollard, 1998; Opheim and Gudmundsson, 1989; Mastin and Pollard, 1988; Peacock and Parfitt, 2002; Lanzafame et al., 2003). The 2003 eruptive event on Gamalama which lasted for more than 2 months with a series of strong explosions, ashy columns up to 2 km, and reported pyroclastic flow, may have been associated with the fracture formation. When considering the faultlines of the entire Gamalama edifice (Fig.9), one can notice that the summit southwest fracture that constitutes the main degassing zone, is associated with the NNE-SSW faults that extend over the entire volcano. Similarly, the large lava flow of 1907 was originated from a NNE-SSW fault. It is thus likely that these NNE-SSW faults constitute the surface manifestation of a larger fault that intersects the Gamalama volcano and subsequently facilitate shallow dyke emplacement. Such a fault direction can be associated with the eastward thrusting of the North Maluku region in response to the convergence within the Molucca Sea (Hamilton, 1979; Cardwell et al., 1980; Hirschberger et al., 2005; Passarelli et al., 2018). This latter geodynamic context triggers more than 150 seismic events ($M \geq 4$) per year within the 200 km radius around Gamalama (<https://earthquake.usgs.gov/>), with possible influence on Gamalama activity (Sinaga et al., 2017).

5. Conclusion

The gas composition obtained at the summit of the Gamalama volcano indicates a prevalent hydrothermal origin, as highlighted by the prevalence of H_2S over SO_2 ($H_2S/SO_2 = 2-8$) and a high CO_2/SO_2 ratio of 76-201. A relative variation in gas composition at different measurement points is observed, due to spatial heterogeneities in the extent of S scrubbing along the degassing fracture zone. The heat transferred to the surface by the system corresponds to only 3.0 MW, in accord with the dominance of hydrothermal

processes. However, the high gas equilibrium temperature of 425-480°C, and the presence of low but measurable SO₂, indicate that ascending fluids are not exclusively derived from a boiling hydrothermal aquifer, but rather require a continuous fluids supply from the basaltic magma to the system. Surface degassing activity on Gamalama has persisted for nearly two decades, a period during which an elevated number of eruptions were witnessed on the volcano. We propose that the large summit fractures, developed since 2002, possibly in response to the regional geodynamics may have weakened the hydrothermal seal, ultimately allowing the pressure build-up in the hydrothermal system, promoted by ascending magmatic gases and by the high annual rainfall, to more easily (and rapidly) exceed the tensile strength of the seal, leading to frequent phreatic eruptions.

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Tables and captions

Table 1. Radiant flux from Gamalama volcano.

Main Crater				Southern fracture zone			
Zone of interest (m ²)				2186			
Temp. range	Corrected mean temp. (°)	Surface per Temp. range (%)	Mean Radiant flux (MW)	Temp. range	Corrected mean temp. (°)	Surface/Tem p. range (%)	Mean Radiant flux (MW)
32-35 °C*	102.9	17.5	2.0	35-40 °C*	107.3	12	0.23
36-40 °C	106.1	4.9	0.6	41-45 °C	111.2	1.8	0.07

41-45 °C	109.7	0.5	0.06	46-50 °C	114.8	0.3	0.01
46-50 °C	113.3	0.2	0.03	51-55 °C	118.4	0.1	0.00
> 51°C	117.7	0.1	0.01	> 56°C	124.8	0.0	0.00

Total Radiant flux (MW) = 3.0 ± 0.9

* values below 32°C and 35°C for the main crater and the southern fracture zone were considered as background since it was not possible to well discriminate the heated surface.

380 **Table 2.** The Gamalama gas composition and ratios at three different locations.

Recording point	MG1	MG2	MG3
Gas Concentration			
H2O (ppm v)	7000-14000	3000-12000	1000-7000
CO2 (ppm v)	450-770	390-550	360-490
SO2 (ppm v)	0.05-0.13	0.2-1.2	0.3-1.6
H2S (ppm v)	0.3-0.4	0.4-6.5	0.1-2.9
H2 (ppm v)	2.0-4.0	0.6-4.0	0.0-3.5
Gas ratios			
H2O/SO2	-	5895 ± 2979	3169 ± 1144
CO2/SO2	-	201 ± 50	76 ± 12
H2S/SO2	-	7.9 ± 0.9	2.5 ± 0.3
H2/SO2	-	1.4 ± 0.9	1.2 ± 1.0
Gas composition		Composition (mol%)	
	H2O	97.5	
	CO2	2.3	
	SO2	0.03	
	H2S	0.08	
	H2	0.04	

Table 3. SO₂ flux obtained during the Jul. 2015 eruption.

19 Jul. 2015				20 Jul. 2015				21 Jul. 2015			
Scan	Start time	Flux (t/d)	Error (%)	Scan	Start time	Flux (t/d)	Error (%)	Scan	Start time	Flux (t/d)	Error (%)
1	11:22:03	2006	26	1	11:32:41	955	10	1	14:51:27	1284	29
2	11:24:01	2615	31	2	11:37:34	923	10	2	14:55:35	1180	30

3	11:25:56	2459	26	3	11:42:41	593	10	3	14:59:29	1344	30
4	11:27:52	1980	31	4	11:47:36	337	10	4	15:04:20	1062	35
5	11:29:47	2106	36	5	11:52:15	477	4	5	15:11:37	1124	29
6	11:31:41	2027	36	6	11:56:43	664	10	Mean value 1199±372 t/d			
7	11:33:36	1886	31	7	12:01:17	855	10				
8	11:35:32	1900	20	8	12:05:57	1582	6				
9	11:37:29	1669	15	9	12:10:43	1562	4				
10	11:39:25	1530	4	10	12:15:18	549	10				
11	11:41:18	1277	42	11	12:19:52	881	10				
12	11:43:15	1089	4	12	12:24:22	342	10				
13	11:45:12	872	31	13	12:28:49	1597	10				
14	11:47:09	838	26	14	12:33:19	385	10				
15	11:49:04	1098	4	15	12:37:51	617	10				
16	11:50:58	1182	1	16	12:42:33	1237	10				
17	11:52:54	1328	1	17	12:47:08	785	10				
18	11:54:50	1566	26	18	12:51:37	1123	10				
19	11:56:58	1772	4	19	12:56:39	796	10				
20	11:58:45	1889	4	20	13:01:17	1083	10				
Mean value 1654±331 t/d				21	13:05:57	815	10				
				22	13:10:36	1147	10				
				23	13:15:33	1318	10				
				24	13:20:10	2240	10				
				25	13:24:47	602	10				
				26	13:29:28	331	10				
				27	13:34:22	482	10				
				28	13:39:01	223	10				
				29	13:43:37	162	10				
				30	13:48:09	882	10				
				Mean value 851±76 t/d							

Mean SO₂ flux: 1235 ± 260 t/d

Figure 1. Gamalama is one of the active volcanoes of Indonesia, highlighted by the red dots (A). It is one of the five active volcanoes of the Halmahera arc, including Dukono, Ibu, Gamkonora and Makian (B). Situated of the coast of Halmahera island (C), Gamalama is a 12 km width volcano off the coast of Halmahera island. The volcano hosts a large city of Ternate with its ~200,000 inhabitants (D). The summit cone of Gamalama is ~1 km in diameter and culminates at 1715 m (E)

Figure 2. Heat distribution at the summit of Gamalama volcano (A) is highlighted by the by thermal mosaic pictures. The heated surface is confined to the western part of the crater (B). The position of the IR camera is provided with the viewing direction to the north at IR_pt1 and to the south at IR_pt2 (C). The bottom picture (C) shows the southern fracture zone. The associated thermal image imphasize the gas influence on the thermal radiation. The temperature near the degassing vents fluctuated around 100°C whilst the thermal image show a relatively cold fracture zone.

Figure 3. (A) Variation of gas concentrations obtained at 3 different points (MG1, MG2, and MG3) at Gamalama summit (B). MG2 position is directly in the plume, compare to MG3, but this latter is close enough to capture the composition of single puffs. MG1 is situated outside the main active zone.

Figure 4. Correlation between H₂O, CO₂, H₂S, and H₂ with SO₂ for MG2 (black dots) and MG3 (red dots). H₂S vs. SO₂ shows a clear change in concentration between MG₂ and MG₃ (A). A similar change is highlighted by CO₂ (B) vs. SO₂. There is a shift towards lower H₂O concentration between MG2 and MG3 and a slight change of H₂O/SO₂ ratios (C). H₂ also shows a shift in concentration between MG2 and MG3 but the H₂/SO₂ ratios are comparable (D). Note that there is no gas correlation at MG1.

Figure 5. (A) CO₂-H₂O-S_T discriminates the hydrothermal gas composition from Gamalama and Papandayan (Fisher and Chiodani, 2015), in comparison to the magmatic gas from other volcanoes in Indonesian, including Merapi (Fisher and Chiodini, 2015), Bromo (Aippa et al., 2015), Sirung (Bani et al., 2017), Dukono (Bani et al., 2018) and Gamkonora (Saing et al., 2020). B) The CO₂/ST vs. Gas temperature (T°C) suggest contributions from hydrothermal and magmatic fluids at Gamalama and Papandayan but the former plot closer to the magmatic group that includes Bromo, Merapi, Gamkonora, Sirung and Dukono.

Figure 6. Fresh rock samples collected during this work at the summit of the Gamalama volcano indicate a basaltic magma composition (black triangle - 2018). The compositions of the 1907 lava flow and the

ejected material of the 1990 eruption (Mawardi et al., 1991) are also of basaltic composition. The less differentiated melt source on Gamalama contrasts with the more differentiated magma on other volcanoes of Halmahera arc, including Gamkonora (stars), Dukono (dots), and Ibu (squares).

Figure 7. (A) Gamalama eruptive event of VEI 1 to 3 since 1510. The cumulative values highlight two periods of an increasing number of eruptive events. The first increase occurred in the mid-19th-Century in concomitant with the establishment of the Dutch colony may merely reflect improved observation and reporting. The second and most recent increase coincides with the fracture formation between 2002 and 2019, in which red bars correspond to magmatic event whilst yellow bars emphasize the phreatic events. (B) The main active zone has shifted over the same period, from the central unique active vent to the peripheral fractured active zones. The charts are made based on available satellite pictures in Google Earth.

Figure 8. The magmatic fluid injected into the hydrothermal system may lead to rock alteration and sulfur precipitates, leading to the formation of a hydrothermal seal that subsequently controls the eruptive activity on Gamalama. The pressure developed by the hydrothermal system may exceed the tensile strength of the seal, leading to a phreatic event.

Figure 9. Faultlines on Gamalama volcano, highlighted by google relief map, clearly emphasize that the summit southwest fracture zone (small red line) that constitutes the main degassing zone, is associated with large NNE-SSW faults. Similarly, the large and most recent lava flow that reached the coast in 1907 was also originated from the NNE-SSW faults.















