Geoscience Letters

RESEARCH LETTER

Open Access

Bromo activity over the last decade: consistent passive degassing and source magma evolution

Hilma Alfianti[1*], Philipson Bani[2], Mamay Sumaryadi[1], Sofyan Primulyana[1], Mita Marlia[1], Ugan B. Saing[1], Nia Haerani[1] and Hendra Gunawan[1]

Abstract

Bromo is among the very active volcanoes in Indonesia and is known for its recurrent and long-lasting eruptive manifestations. Past volcanic gas studies have revealed Bromo as one of the principal sources of volcanic degassing in Indonesia. This high degassing from Bromo volcano is further characterized in this work, based on more than 10 years of intermittent ground-based gas measurements, combined with daily SO_2 mass, captured by the OMI sensor. Over the past decade, Bromo has released 0.7 Tg of SO_2 into the atmosphere, representing 3% of the volcanic degassing budget of Indonesia and 0.3% of the global volcanic SO_2 emission budget outside eruptive periods. Results also reveal that 18.8 Tg of H_2O, 2.0 Tg of CO_2, 0.1 Tg of H_2S, and 0.005 Tg of H_2 were released from the Bromo volcano in one decade. About 81% of these gases are released passively between eruptive events. The chemistry of the eruptive products, sampled between 2001 and 2019, indicate that Bromo volcanic activity is sustained by a basaltic-andesite to basalt trachy-andesite magma source with a transition from medium-K to high-K composition. Such an evolution associated to a C-rich gas likely resulted from a low partial melting and sediment contribution to the genesis of the source magma. New magma injections into the reservoir and fractional crystallization have further amplified the changes of magma composition. Finally, we speculate that the shallow reservoir replenishment, in response to the continuous strong degassing is the driving mechanism behind the Bromo frequent eruptive events.

Keywords: Bromo volcano, Consistent strong degassing, Medium-K to high-K melt source

Introduction

Bromo is one of the most active volcanoes in Indonesia, located on the eastern part of Java Island (Fig. 1) (Coord. 7.942°S/112.953°E). Over the last two centuries, more than 50 eruptions have been recorded on this volcano (GVP 2013), which broadly correspond to one eruption every three years. It is still unclearly when the volcanic activity commenced on Bromo, but according to ^{14}C datings, it has been active since the seventeenth century (Zaenudin 1990; Mulyadi 1992) and it is the most recent cone, formed after the Tengger Caldera formation, more than 45,000 years ago (van Gervan and Pichler 1995). Bromo is currently the only active cone in Tengger caldera with an open-vent activity that channels a continuous degassing into the atmosphere. It constitutes, with 4 other cones, namely Watangan, Widodaren, Sagarawedi, and Batok (Fig. 1), a volcanic complex in the caldera whose tephra deposits have filled the caldera floor and formed the so-called "sand sea caldera" (Abidin et al. 2004). Few available gas studies have evidenced Bromo as a strong source of volcanic degassing with a daily SO_2 emission rate varying between 14 and 166 t d^{-1}(Andres and Kasgnoc 1998; Bani et al. 2013; Aiuppa et al. 2015). The gas composition with its magmatic signature

*Correspondence: hilmaalfianti8@gmail.com
[1] Center for Volcanology and Geological Hazard Mitigation, Geological Agency, Ministry of Energy and Mineral Resources of Indonesia, Jl. Diponegoro no. 57, Bandung, Indonesia
Full list of author information is available at the end of the article

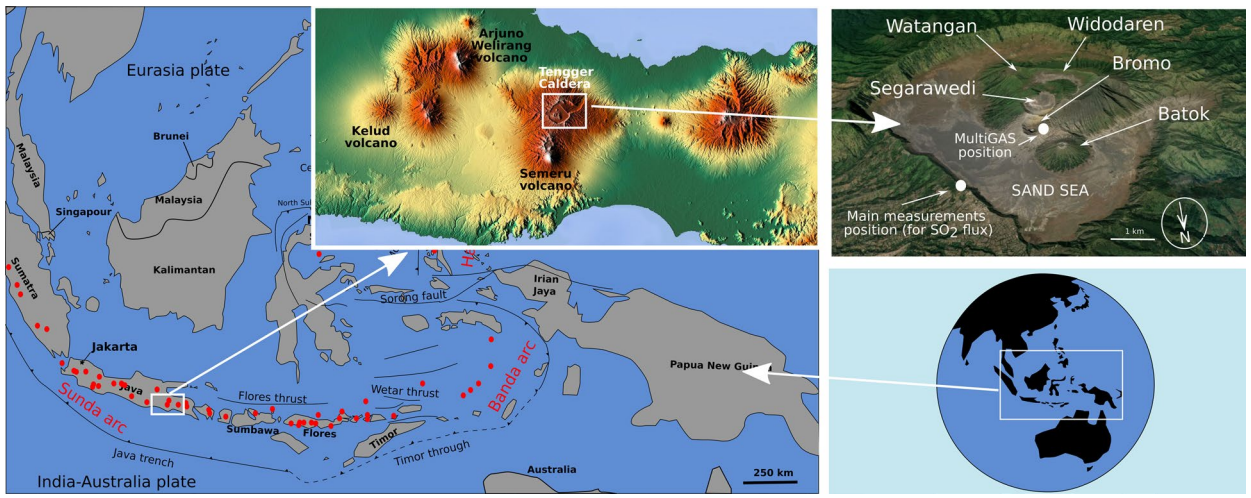

Fig. 1 Bromo is located on the eastern part of Jawa Island. It is one of the post-caldera active cones, including Segarawedi, Watangan, Widodaren, and Batok (upper right). Bromo is the only current active cone in the sand sea caldera. The main point for static SO_2 flux measurements is highlighted (upper right). Red dots denote active volcanoes of Indonesia only

indicates a water-rich magma, typical of arc volcanoes and a CO_2/S_T ratio of 3.2 (Aiuppa et al. 2015), comparable to the mean value of 4.3 for the Indonesian magmatic gas (Hilton et al. 2002), and suggests a contribution of carbon-rich sediments to the magma genesis (Aiuppa et al. 2017).

This work aims to characterize the evolution of volcanic degassing from Bromo and to determine how it relates to the subsurface magmatic processes based on the chemistry of the erupted products.

Methods

The first ground-based SO_2 flux measurements on Bromo were carried out in March 1995 using the correlation spectrometer (COSPEC) (see McGonigle and Oppenheimer 2003 for technical details). The instrument was positioned 2 km northeast of the cone, on the rim of the sand sea caldera, and performed a scan across the rising plume. Over the last 15 years, Bromo's SO_2 emission rate has regularly been measured, using a flyspec (e.g., Horton et al., 2006) since 2005, a DOAS (differential optical absorption spectroscopy; Galle et al. 2003) since 2013 (Bani et al. 2013), and a UV-Camera (Mori and Burton 2006) since 2014 (Aiuppa et al. 2015). These different approaches were carried out on a static mode at 2 km northeast of the active crater, at a similar position of COSPEC measurements in 1995 (Fig. 1). Wind speed was obtained either from the handheld anemometer for the early measurements or from cameras in the recent recordings (Tamburello et al. 2011). The most recent SO_2 flux measurements were carried out in 2018 and 2019 using a scanning DOAS, on a fix-position at 2 km northeast of the Bromo cone. The spectrometer used was an Ocean Optic USB2000+with a spectral range of 280–440 nm and 0.5 nm FWHM (Bani et al. 2013, 2017). The scanning step angle was 1°. The SO_2 column amounts were retrieved using DOAS standard analysis procedures (Platt and Stutz 2008). The reference spectra included in the nonlinear fit were obtained by convolving high-resolution SO_2 (Bogumil et al. 2003) and O_3 (Voigt et al. 2001) cross-sections with the instrument line shape. A Fraunhofer reference spectrum and a ring spectrum, calculated in DOASIS (Krauss 2005), were also included in the fit. The total column amount is then multiplied with the mean plume speed (estimated at 1 m/s using a thermal camera) to obtain the SO_2 flux. To assess the fluctuation of the SO_2 emission from Bromo over a longer time series (Fig. 2), the SO_2 mass captured by the ozone monitoring instrument (OMI), available online (https://so2.gsfc.nasa.gov/index.html) were compiled and analyzed following the approach in Bani et al (2016) (see Additional file 1: 1).

Bromo gas composition was first obtained in 2014 (Aiuppa et al. 2015) using the multicomponent gas analyzer system (Multi-GAS) (Aiuppa et al. 2005; Shinohara 2005). The same instrument was again deployed in 2018 (this work) and positioned downwind side of the Bromo crater rim. The unit simultaneously measured the concentrations of H_2O, CO_2, SO_2, H_2S, and H_2 at 0.5 Hz. Water (H_2O) and CO_2 were detected by nondispersive infrared spectroscopy (LI-COR LI-840A; 0–60,000 ppm range). While SO_2, H_2S, and H_2 were measured using electrochemical sensors, respective models 3ST/F, EZ3H, and EZT3HYT Easy Cal from City Technology with the measurement range of 0–200 ppm. The data were

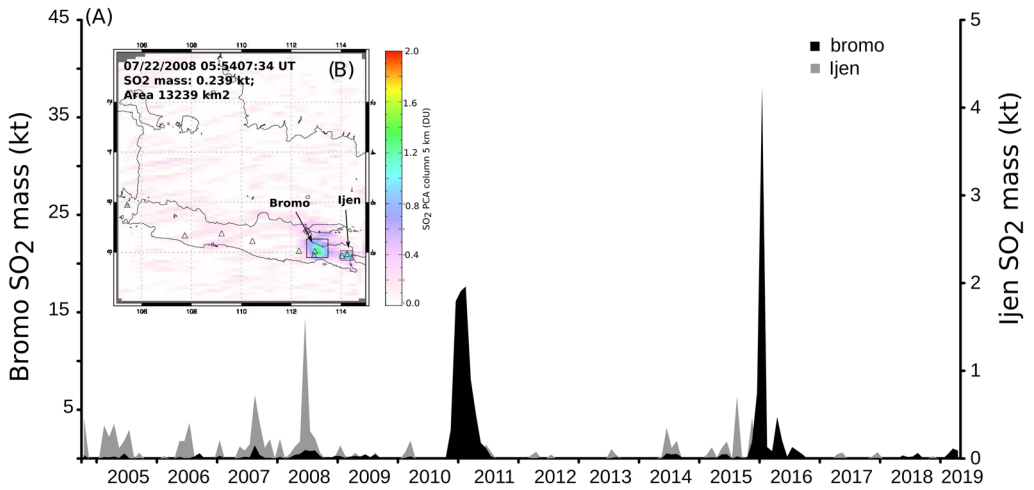

Fig. 2 **A** The graph highlights the proportions of simultaneous SO_2 occurrence from Bromo and Ijen volcanoes. **B** The daily OMI image covers all the volcanoes of Java island. However, Bromo and Ijen are the main degassing sources. Their plume dispersals can be easily discriminated on each OMI image and their extents are manually delimited. The thumbnail image of July 22, 2008 is provided as an example

processed and analyzed for the molar ratios between different volatile species using the Ratiocalc software (Tamburello 2015).

To gain further insights into the magmatic source behind the Bromo activity, ash and scoria deposits from 2000–2001, 2010–2011, 2015–2016, and 2019 eruptions were sampled then analyzed for major elements in the laboratory using X-ray fluorescence (XRF). Results were then compared to available data in the literature.

Results and discussion

Persistent strong passive degassing

Ground-based SO_2 flux measurement results on Bromo since the first recording in 1995 are summarized in Additional file 1: Table S2, highlighting a persistent passive degassing into the atmosphere. The first mean value of 14 t day^{-1} obtained from COSPEC recordings is one to two orders of magnitude lower than the recent estimates but comparable to the incomplete DOAS traverse results from Bani et al. (2013). Using this unique SO_2 flux value available in the mid-1990s, Andres and Kasgnoc (1998) have classified Bromo (Tengger Caldera) in the 46th position out of 49 main volcanic gas contributors into the atmosphere. If we assume that such a relatively small gas emission can be representative of Bromo activity in the 1990s, then the corresponding magma source must be less-rich in gas content. However, if the COSPEC and DOAS traverse results are excluded, then the daily emission rate outside the eruptive periods from Bromo fluctuates between 82 and 280 t with a mean value of 181 ± 60 t day^{-1}. This degassing value is consistent over the last 15 years of ground-based measurements (Additional file 1: Table S2, Fig. 3), which thus confirms Bromo as one of the strong and persistent degassing sources in Indonesia. When integrating our result into the recent global volcanic SO_2 emission budget from Carn et al. (2017), Bromo would rank 68th out of the 91 listed volcanoes, comparable to the degassing of Stromboli volcano (181 t day^{-1}). Assuming that our result is representative, then the mean annual SO_2 contribution into the atmosphere from Bromo is ~ 0.07 Tg, representing 2.3% of the annual contribution from Indonesian volcanoes (Fischer et al. 2019) and 0.3% of the annual global volcanic SO_2 emission budget (Carn et al. 2017).

Eruptive gas contribution

In the recent inventory of volcanic gas emissions, based on OMI satellite data, Carn et al. (2017) rank the combined SO_2 emission budget from Bromo and Semeru volcanoes on the 20th position out of 91 identified volcanic degassing sources worldwide, with a daily mean value of 775 t, much higher than the mean passive degassing of 181 t obtained in this work. It is also higher than the ground-based SO_2 fluxes obtained during the winding down phases of the 2015–2016 eruption (Additional file 1: Table S2, Fig. 3) that fluctuated between 130 and 440 t day^{-1}. When comparing the SO_2 mass obtained from OMI and the ground-based DOAS measurements (Fig. 3) outside the eruptive periods, the OMI values are systematically lower than the DOAS results. Moreover, Smekens et al. (2015) estimated a daily SO_2 release from Semeru to be $21-71$ t using a UV-Camera. If the ground-based estimates of Bromo were combined with Semeru results, assuming that these figures are

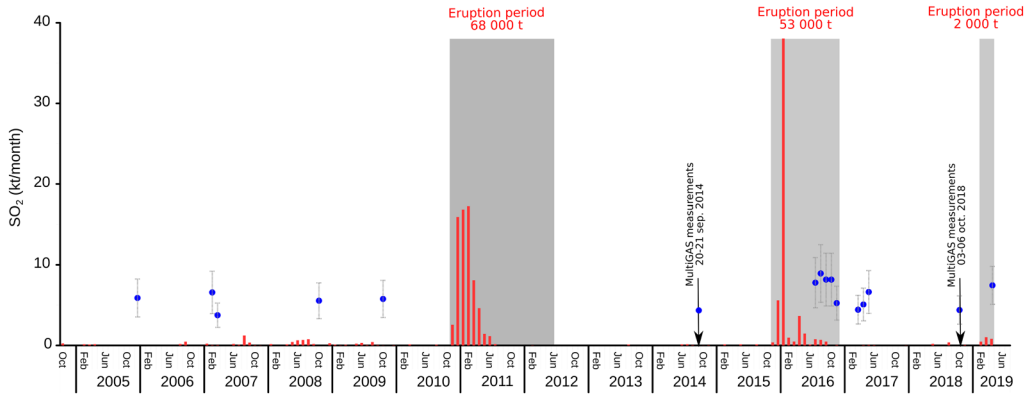

Fig. 3 Ground-based SO_2 flux results since 2005 (blue points) combined with OMI SO_2 mass discharge from Bromo over the same period (2005 – 2019). The total SO_2 mass discharge per eruption is obtained by summing the daily SO_2 mass over the eruption period (in gray). The two multiGAS measurement points are indicated and correspond to the period of 20–21 Sep. 2014 and 03–06 Oct. 2018

representative, then the total contribution outside the eruptive period from these two volcanoes would be about 200 – 250 t day^{-1}, with Bromo being the main degassing source, representing > 70% of the total SO_2 output. One alternative explanation of this difference would be an overestimation of SO_2 mass discharges from the OMI data, due to the eruptive discharges that can last from a few to more than ten months at Bromo.

Between 2009 and 2019, Bromo experienced three distinct eruptive events: in 2010 – 2011 (8 months), in 2015 – 2016 (11 months), and 2019 (3 months) with the corresponding SO_2 mass discharges of 68 kt, 53 kt, and 2 kt, respectively (Fig. 3). Thus a total of 123 kt of SO_2 mass was released from Bromo during the eruptive events over the last decade, a figure that corresponds to 19% of the total SO_2 contribution into the atmosphere. In comparison, more than 532 kt of SO_2 were released through passive degassing over the same period, representing 81% of the total SO_2 emission budget. The main SO_2 contribution to the atmosphere from Bromo is thus through passive degassing, as already seen on other volcanoes (e.g.,Andres and Kasgnoc 1998; Bani et al. 2012).

Gas composition and emission budget

Multi-GAS measurement results obtained in October 2018 are comparable to Aiuppa et al. (2015) findings (Table 1; Fig. 4) with H_2S/SO_2, CO_2/SO_2, H_2/SO_2, and H_2O/SO_2 ratios, obtained from the best-fit regression lines of 0.2 – 0.5, 3.6 – 5.0, 0.1 – 0.4, and 61 – 142 over 3 days of field measurements. Note that on the 3rd day

Table 1 Bromo volcanic gas ratios, gas composition, and degassing budget

Date	H_2S/SO_2	CO_2/SO_2	H_2/SO_2	H_2O/SO_2	Source
20/09/2014	0.35 ± 0.07	3.6 ± 1.0	0.14 ± 0.05	61 ± 16	Aiuppa et al. (2015)
21/09/2014	0.18 ± 0.08	4.6 ± 1.8	0.29 ± 0.17	142 ± 54	
03/10/2018	0.44 ± 0.02	3.9 ± 0.9	0.24 ± 0.07	137 ± 51	This work
05/10/2018	0.53 ± 0.003	5.0 ± 3.1	0.38 ± 0.16	64 ± 37	
06/10/2018	0.46 ± 0.01	–	–	–	
Mean	0.39 ± 0.04	4.3 ± 1.7	0.26 ± 0.11	101 ± 39	
Mean CO_2/S_T	3.1 ± 1.6				

Gas composition and mean flux estimates

	Composition (mol %)	Flux (t/d)
H_2O	94.4	5141 ± 658
CO_2	4.0	532 ± 70
SO_2	0.9	181 ± 60
H_2S	0.4	37 ± 12
H_2	0.2	1.0 ± 0.2

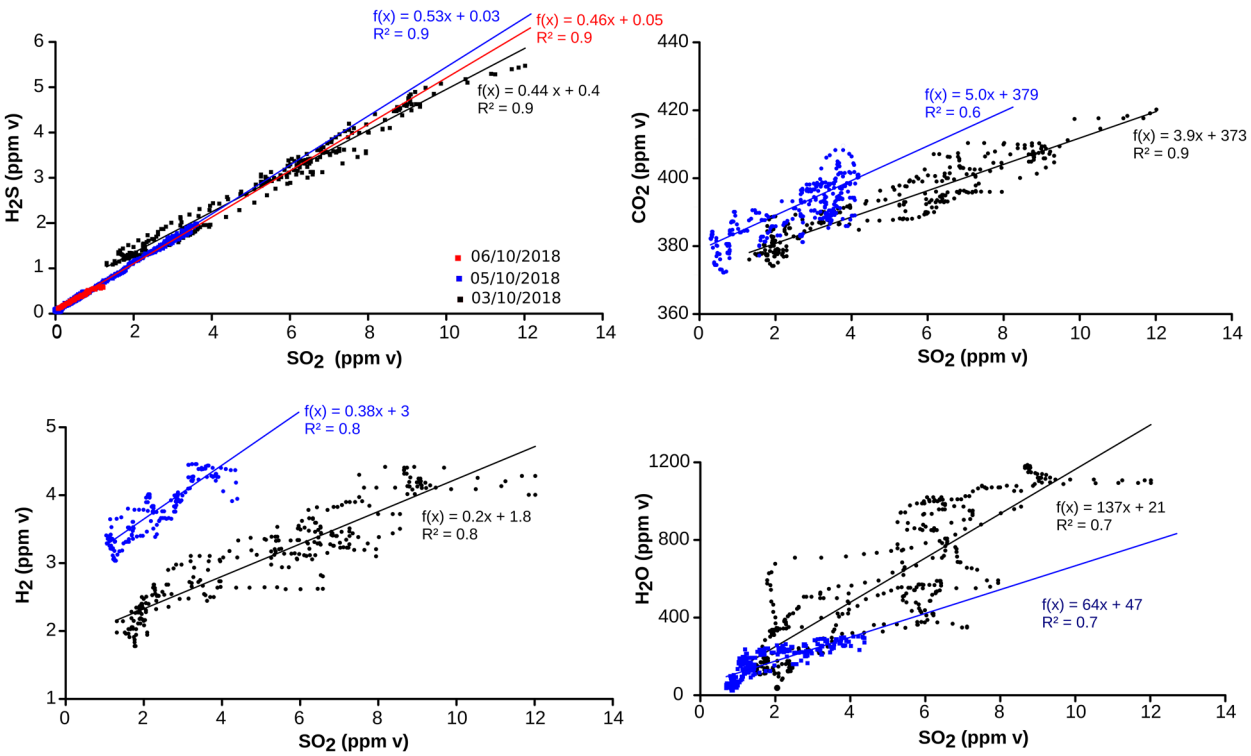

Fig. 4 Gas to SO_2 linear correlation from the Multi-GAS measurement on 03/10/2018 (black points), 05/10/2018 (blue points) and 06/10/2018 (red points). Due to the change of wind direction on 06/10/2018, only the diluted part of the plume reached the Multi-GAS allowing only the H_2S/SO_2 ratio to be retrieved with acceptable correlation value

of gas measurements (06/10/2018), the wind direction changed, allowing only the diluted part of the plume to reach the Multi-GAS. Thus only the H_2S/SO_2 ratio was retrieved with an acceptable correlation value. If combining the results from Aiuppa et al. (2015) with this 2018 results, one can obtain the mean values of 0.39 ± 0.04, 4.3 ± 1.7, 0.26 ± 0.11, and 101 ± 39 for H_2S/SO_2, CO_2/SO_2, H_2/SO_2, and H_2O/SO_2, respectively (Table 1). The prevalence of SO_2 over H_2S and the high equilibrium temperature of circa 699 °C 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), suggests that Bromo gas emissions are fed by a magmatic source with redox conditions between FeO–Fe_2O_3 and nickel–nickel oxide buffers (NNO) (oxygen fugacity of 10^{-16} bars). The mean CO_2/S_T ratio is 3.0 ± 1.6, S_T being the combined H_2S and SO_2 molar values. This value is above the mean CO_2/S_T ratio (~2) for persistently degassing at open-vent arc volcanoes (Shinohara 2013), but is well within the range of volcanic gas CO_2/S_T ratios of 3−6 of Java volcanoes (Aiuppa et al. 2015). This C-rich gas composition implies some substantial carbon contribution from either the slab or the crustal-derived fluids (Aiuppa et al. 2017, 2019) into the source mechanism, however further work is required to better constrain this C-enrichment. By converting the measured volatile ratios into molar percentages (in the assumption that no other major volcanogenic gas is present in addition to those determined), it is found that Bromo releases a water-rich gas with 94.4% H_2O molar proportion, typical for arc volcanic gases (Fischer 2008). The inferred concentrations for the other gases are 4.0%, 0.9%, 0.4%, and 0.2% for CO_2, SO_2, H_2S, and H_2, respectively (Table 1). When combining the gas ratios and the mean SO_2 flux of 181 ± 60 t day^{-1}, the daily passive emission for each gas component would be 5141 ± 658 t, 532 ± 70 t, 37 ± 12 t, and 1.0 ± 0.2 t for H_2O, CO_2, H_2S, and H_2, respectively. If these results are extrapolated over the last 10 years, then the total magmatic gas contribution into the atmosphere from Bromo over the last decade would be 18.8 Tg for H_2O, 2.0 Tg for CO_2, 0.7 Tg for SO_2, 0.1 Tg for H_2S, and 0.005 Tg for H_2. Bromo is thus a non-negligible source of magmatic volatile contributions into the atmosphere.

With 0.2 Tg CO_2 year^{-1}, Bromo is also a strong CO_2 degassing source, representing ~3% of the Indonesian volcanic CO_2 contribution into the atmosphere (7.5 Tg CO_2 year^{-1}; Fischer et al. 2019) and ~0.4% of the global

volcanic CO_2 emission budget (51.3 Tg year^{-1}) outside eruptive periods. Of course, this natural CO_2 emission remains negligible compare to the 460 Tg of CO_2 release each year by coal and oil power plants in Indonesia (https://www.iea.org/).

Degassing source

The scoria and ash samples collected during four past eruptive events (2000–2001, 2010–2011, 2015–2016, and 2019 eruptions) were analyzed for their major elements. Results (Additional file 1: Table S3) indicate a basaltic-andesite to basalt trachy-andesite melt source beneath the Bromo volcano, with a transition from a medium-K to a high-K composition (Fig. 5) over the last 20 years. Eruptive products from the 2000–2001 event are of medium-K signature. Those from the 2010–2011 eruption display a wide range from medium-K to high-K, and the products from 2015–2016 and 2019 eruptions highlight high-K composition. The eruptive products from the 2000–2001 event are well discriminated in the FeO*–(K_2O+Na_2O)–MgO diagram (Fig. 5), and they emphasize a tholeiitic affinity while the material from the other eruptions plot along the transition line between the tholeiitic and calc-alkaline series (Fig. 5). Such an evolution of rock composition was reported in the past works (Whitford et al. 1979; Van Gerven and Pichler 1995; Santoso et al. 2017) and the medium-K rocks were attributed to pre-caldera activities while in contrast, the high-K affinity samples were considered to be induced by the younger and post-caldera magma. Van Gerven and Picher (1995), who also observed the co-occurrence of these two magma affinities on Bromo, indicate that the calc-alkaline rocks would not be expected as a function of the depth of the Waditi-Benioff zone.

Over the last 20 years, the SiO_2 obtained from the eruptive products is virtually unchanged, between 53 and 57 wt%. Such character is generally encountered on volcanoes with a tholeiitic affinity (e.g., Rogers 2015; Chin et al. 2018). When referring to MgO as a fractional crystallization index, knowing that its content in the melt decreases with the cooling and crystal removals from the gradually solidifying melt (e.g., Rogers 2015), it appears that the 2000–2001 eruption was likely sustained by an evolved magmatic source, given its low MgO content (1.4–2.0 wt%) and a relatively high P_2O_5 (0.12–0.49 wt%), SiO_2 (53.8–57.21 wt%), and CaO (8.5–9.9 wt%). In an open-vent system, such a scenario is symptomatic of a magma that has released much of its gas. The low SO_2 flux (6–23 t/day) recorded in 1995 (Additional file 1: Table S2) was likely sustained by this same degassed melt source. In contrast, the 2010–2011 eruption displays a higher MgO content (1.8–3.2 wt%) but relatively low CaO (6.2–7.2 wt%), and SiO_2 (53.2–56.6 wt%) contents indicating a less evolved magmatic source. Such a change in magma composition suggests a possible new magma supply into the reservoir. The wide ranges of CaO, Al_2O_3, TiO_2, SiO_2, Na_2O, P_2O_5, and even K_2O, indicate that this new magma supply was injected into a relatively evolved melt source (e.g., Cassidy et al. 2018). The high amount of SO_2 discharge (68 kt) (Fig. 3) during this 2010–2011 eruption supports the idea of this new magma injection. The strong increase in K_2O observed in 2010

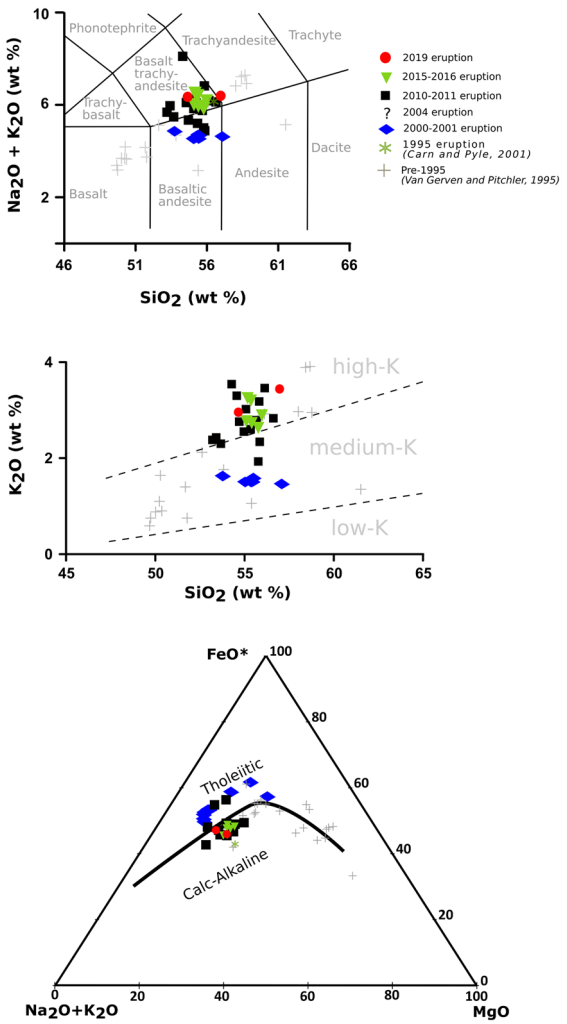

Fig. 5 Bulk analysis results from ash samples collected during eruptive events. The total alkaline vs SiO_2 indicates a basaltic-andesite to basalt trachy-andesite source (top) with a clear transition from medium-K to high-K melt source in the very recent period of Bromo activity (middle). The AFM diagram (bottom) (Irvine and Baragar 1971) highlights the transition between the tholeiitic and calc-alkaline sources. Data from Van Gervan and Pitchler (1995) and Carn and Pyle (2001) are plotted as references. Note that there are no data from the 2004 eruption

compared to 2001 is another evidence of a new magma injection but with the assumption that the magma genesis involves a low degree of partial melting (Schiano et al. 1998), knowing that K can be easily mobilized by incoming fluid. In such a scenario, a variable degree of partial melting may be responsible for the transition from medium- to high-k magma source (Whitford et al. 1979) on Bromo. The fluid responsible for the partial melting is likely induced by the dehydration of the subduction slab with a contribution of subducted sediments that are possibly enriched in carbon, given the relatively high CO_2/S_T ratio. A sediment contribution to the magma genesis is described by Gertisser and Keller (2003) to be responsible for the compositional contrast between medium-K and high-k magma on Merapi volcano. The sediment contribution and the variability of partial meting may contribute to the changes of magma composition on Bromo volcano as well, but further isotopic analyses would be needed to corroborate such interpretation.

The SO_2 flux obtained between 2005 and 2009 (Additional file 1: Table S2) fluctuates between 112 and 281 t d^{-1}, which is an order of magnitude higher than the 1995 values. Furthermore, according to the history of Bromo eruptive activities (GVP 2013), there was a strong eruptive event in June 2004 that built a large and dense column of ash up to 3000 m above the crater GVP 2004). Similarly to 2010, such an intense manifestation requires a new magma supply into the reservoir. Unfortunately the tephra products from this event are not available for this study. However given the low SO_2 flux recorded before the eruption (14 t day^{-1} in 1995), the high intensity of the 2004 eruption followed by a persistent high SO_2 flux, and also the evolved and degassed source observed during 2000–2001 eruption, it is likely that Bromo volcano has also witnessed a new magma injection in 2004. Both these two new magma supplies (in 2004 and 2010–2011) are consequently responsible for the persistent strong degassing that we observed over the last decade. The compositions of the ejected products from the 2015–2016 and 2019 eruptions fall in the range of 2010–2011 products suggesting a unique magmatic source, in agreement with the unchanged gas composition obtained in 2014 (Aiuppa et al. 2015) and 2018 (Table 1). The relative increase in concentrations of oxides, between the 2015–2016 and the 2019 eruptions, highlighted by K_2O (from 2.6–3.2 to 3.0–3.5 wt%), P_2O_5 (from 0.31–0.35 to 0.37–0.47 wt%), SiO_2 (from 55.3–55.9 to 54.6–56.9 wt%) or TiO_2 (1.01–1.09 to 1.09–1.13 wt%) indicate a relative fractional crystallization. The decrease of eruptive SO_2 mass discharge, from 53 kt during the 2015–2016 eruption, to 2 kt during the 2019 event, also reflect the evolution within the same melt source (Additional file 1: Table S2, Fig. 3).

Considering the hyperactivity of this volcano (50 eruptions in 2 centuries), frequent pressurization of the shallow reservoir is required. Although it is obvious that a new magma injection plays a major role in Bromo hyperactivity, it is unlikely that such magma supply constitutes the unique triggering factor of all the eruptions. We speculate that the progressive replenishment of a shallow reservoir, in response to the persistently high degassing following the model of Girona et al. (2015) would contribute to the hyperactivity of Bromo while maintaining the continuous strong degassing. In such a scenario the pressure in the shallow reservoir decreases because of degassing. But subsequently, it induces a pressure difference with a deeper reservoir. Thus the depressurization is simultaneously compensated by the pressurization induced by the replenishment process of the yield-stress magma. In such a case, the dike between the two reservoirs is regularly cleared, allowing the deep and shallow reservoirs to be connected leading to a regular pressure buildup in the shallow reservoir and subsequent eruptive events.

Conclusion

Ground-based gas measurements combined with daily satellite recording of SO_2 mass above Bromo Volcano indicate that over the last decade about 18.8 Tg of H_2O, 2.0 Tg of CO_2, 0.7 Tg of SO_2, 0.1 Tg of H_2S, and 0.005 Tg of H_2 were released into the atmosphere. Bromo is thus one of the notable magmatic volatile contributors to the atmosphere, representing 2.3% and 3% of the annual SO_2 and CO_2 emission budgets from Indonesian volcanoes and about 0.3% and 0.4% of the annual global volcanic SO_2 and CO_2 degassing budget outside eruptive period.

Despite the recurrent and long eruptive manifestations, the main volatile contribution into the atmosphere from Bromo is through passive degassing, representing about 81% of the total gas released. The magmatic source that feeds Bromo activity is of basaltic-andesite to basalt trachy-andesite composition with a transition from medium-K to high-K over the last two decades due to the low degree of partial melting and the C-rich sediment contributions to the magma genesis. The moderate fractional crystallization processes and the new magma injections also contributed to the evolution of source magma. Finally, the hyperactivity of the Bromo volcano and its persistent strong degassing is likely sustained by the new magma injections and a progressive replenishment of the shallow reservoir in response to depressurization and pressure buildup initiated by the continuous

strong degassing and the yield-stress magma between the deep and shallow reservoirs.

Competing interest

The authors declare no competing interest.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40562-022-00221-2.

Additional file 1: 1. Retrieving the SO_2 mass over Bromo. **Table S2.** SO_2 Flux Measurements Obtained on Bromo between 1995 and 2019. **Table S3.** Bulk Ash Composition from Bromo Eruptive Activities. **Figure S4.** The Indonesian volcanic degassing sources compare to the main volcanic degassing sources on earth, according to Carn et al (2017). **Figure S5.** Variation in major elements as function of SiO_2 in the eruption products.

Acknowledgements

The authors acknowledge the support from CVGHM (Center for Volcanology and Geological Hazard Mitigation) and IRD, particularly under the JEAI-COMMISSION project. We extend our sincere acknowledgement to the observers of Bromo Volcano for their collaboration and to colleague Estu Kriswati for valuable suggestions and discussion.

Authors' contributions

HA compiled and prepared the dataset, and together with PB, they wrote the major part of the paper. MP and SP provided insights into the ash geochemistry and SO_2 flux data. SP, HA, PB, MM, UBS and NH participated in the field gas measurements and samplings. HG facilitated access to the volcano and contributed to the discussion on the past decade's activity of Bromo. All authors have read and approved the final manuscript.

Availability of data and materials

The datasets during the current study are available from the corresponding author upon reasonable request. Please contact the corresponding author for data requests.

Author details

[1]Center for Volcanology and Geological Hazard Mitigation, Geological Agency, Ministry of Energy and Mineral Resources of Indonesia, Jl. Diponegoro no. 57, Bandung, Indonesia. [2]Laboratoire Magmas Et Volcans, Universite Blaise Pascale–CNRS–IRD, OPGC, 63000 Clermont-Ferrand, France.

Received: 16 December 2019 Accepted: 2 February 2022
Published online: 19 March 2022

References

Abidin HZ, Andreas H, Gamal M (2004) The deformation of Bromo volcano (Indonesia) as detected by GPS surveys method. J Glob Position Syst 3(1–2):16–24. https://doi.org/10.5081/jgps.3.1.16

Aiuppa A, Federico C, Giudice G, Gurrieri S (2005) Chemical mapping of a fumarolic field: La Fossa Crater, Vulcano Island (Aeolian Islands, Italy). Geophys Res Lett 32:L13309. https://doi.org/10.1029/2005GL023207

Aiuppa A, Shinohara H, Tamburello G, Giudice G, Liuzzo M, Moretti R (2011) Hydrogen in the gas plume of an open-vent volcano, Mount Etna, Italy. J Geophys Res B Solid Earth 116(10):B10204. https://doi.org/10.1029/2011JB008461

Aiuppa A, Bani P, Moussallam Y, Di Napoli R, Allard P, Gunawan H, Hendrasto M, Tamburello G (2015) First determination of magma-derived gas emissions from Bromo volcano, Eastern Java (Indonesia). J Volcanol Geotherm Res 304:206–2013. https://doi.org/10.1016/j.jvolgeores.2015.09.008

Aiuppa A, Fischer TP, Plank T, Robidoux P, Di Napoli R (2017) Along-arc and inter-arc variations in volcanic gas CO_2/S_T ratios reveal dual source of carbon in arc volcanism. Earth Sci Rev 168:24–47. https://doi.org/10.1016/j.earscirev.2017.03.005

Aiuppa A, Fischer TP, Plank T, Bani P (2019) CO_2 flux emissions from the Earth's most actively degassing volcanoes, 2005–2015. Sci Rep 9:5442. https://doi.org/10.1038/s41598-019-41901-y

Andres RJ, Kasgnoc AD (1998) A time-average inventory of subaerial volcanic sulphur emissions. J Geophys Res 103(25):251–261. https://doi.org/10.1029/98JD02091

Bani P, Oppenheimer C, Allard P, Shinohara H, Tsanev V, Carn S, Lardy M, Garaebiti E (2012) First estimate of volcanic SO_2 budget for Vanuatu island arc. J Volcanol Geotherm Res 211–212:36–46. https://doi.org/10.1016/j.jvolgeores.2011.10.005

Bani P, Surono HM, Gunawan H, Primulyana S (2013) Sulfur dioxide emissions from Papandayan and Bromo, two Indonesian volcanoes. Nat Hazards Earth Syst Sci 13:2399–2407

Bani P, Boudon G, Balcone-Boissard H, Delmelle P, Quiniou T, Lefèvre J, Bule EG, Hiroshi S, Lardy M (2016) The 2009–2010 eruption of Gaua volcano (Vanuatu archipelago): eruptive dynamics and unsuspected strong halogens source. J Volcanol Geotherm Res 322:63–75. https://doi.org/10.5194/nhess-13-2399-2013

Bani P, Alfianti H, Auippa A, Oppenheime C, Sitinjak P, Tsanev V, Saing UB (2017) First study of the heat and gas budget for Sirung volcano, Indonesia. Bull Volcanol 79:60. https://doi.org/10.1007/s00445-017-1142-8

Bogumil K, Orphal J, Homann T, Voigt S, Spietz P, Fleischmann OC, Vogel A, Harmann M, Kromminga H, Bovensmann H, Frerick J, Burrows JP (2003) Measurements of molecular absorption spectra with SCIAMACHY preflight model: instrument characterization and reference data for atmospheric remote sensing in the 230–2380 nm region. J Photochem Photobiol A 157(2–3):167–184. https://doi.org/10.1016/S1010-6030(03)00062-5

Carn SA, Pyle DM (2001) Petrology and geochemistry of the Lamongan Volcanic Field, East Java, Indonesia: Primitive Sunda Arc magmas in an extensional tectonic setting? J Pet 42(9):1643–1683. https://doi.org/10.1093/petrology/42.9.1643

Carn SA, Fioletov VE, McLinden CA, Li C, Krotkov NA (2017) A decade of global volcanic SO_2 emissions measured from space. Sci Rep 7:44095. https://doi.org/10.1038/srep44095

Cassidy M, Manga M, Cashman K, Bachmann O (2018) Controls on explosive-effusive volcanic eruption styles. Nat Commun 9:2839. https://doi.org/10.1038/s41467-018-05293-3

Chin EJ, Shimizu K, Bybee GM, Erdman ME (2018) On the development of calc-alkaline and tholeiitic magma series: a deep crustal cumulate perspective. Earth Planet Sci Lett 482:277–287. https://doi.org/10.1016/j.epsl.2017.11.016

Fischer TP (2008) Fluxes of volatiles (H_2O, CO_2, N_2, Cl, F) from arc volcanoes. Geochem J 42:21–38. https://doi.org/10.2343/geochemj.42.21

Fischer TP, Arellano S, Carn S, Aiuppa A, Galle B, Allard P, Lopez T, Shinohara H, Kelly P, Werner C, Cardellini C, Chiodini G (2019) The emissions of CO_2 and other volatiles from the world's subaerial volcanoes. Sci Rep 9:18716. https://doi.org/10.1038/s41598-019-54682-1

Galle B, Oppenheimer C, Geyer A, McGonigle A, Edmonds M, Horrocks L (2003) A miniaturised ultraviolet spectrometer for remote sensing of SO_2 fluxes: a new tool for volcano surveillance. J Volcanol Geotherm Res 119:241–254. https://doi.org/10.1016/S0377-0273(02)00356-6

Gertisser R, Keller J (2003) Trace element and Sr, Nd, Pb and O Isotope variations in medium-K and high-k volcanic rocks from Merapi volcano, Central Java, Indonesia: Evidence for the involvement of subducted sediments in Sunda Arc magma genesis. J Pet 44(3):457–489. https://doi.org/10.1093/petrology/44.3.457

Girona T, Costa F, Schubert G (2015) Degassing during quiescence as a trigger of magma ascent and volcanic eruption. Sci Rep 5:18212. https://doi.org/10.1038/srep18212

Global Volcanism Program (1995) Report on Tengger Caldera (Indonesia). Bull Glob Volcan Netw. https://doi.org/10.5479/si.GVP.BGVN199503-263310

Global Volcanism Program (2004) Report on Tengger Caldera (Indonesia). Bull Glob Volcan Netw. https://doi.org/10.5479/si.GVP.BGVN200405-263310

Global Volcanism Program (2013) Tengger Caldera (263310) in Volcanoes of the World, v. 4.8.3. Venzke, E (ed.). Smithsonian Institution. https://volcano.si.edu/volcano.cfm?vn=263310. Accessed 22 Sep 2019

Hilton DR, Fischer TP, Marty B (2002) Noble gases and volatile recycling at subduction zones. Rev Miner Geochem 47(1):319–370. https://doi.org/10.2138/rmg.2002.47.9
Horton KA, Williams-Jones G, Garbeil H, Elias T, Sutton AJ, Mouginis-Mark P, Porter JN, Clegg S (2006) Real-time measurement of volcanic SO_2 emissions: validation of a new UV correlation spectrometer (FLYSPEC). Bull Volcanol 68:323–327. https://doi.org/10.1007/s00445-005-0014-9
Irvine TN, Baragar WRA (1971) A guide to the chemical classification of the common volcanic rocks. Can J Earth Sci 8:523–548. https://doi.org/10.1139/e71-055
Kraus S (2005) DOASIS: A framework design for DOAS, Dissertation, University of Mannheim, Germany
McGonigle AJS, Oppenheimer C (2003) Optical sensing of volcanic gas and aerosol emissions. In: Oppenheimer C, Pyle DM, Barclay J (eds) Volcanic degassing. Geological Society, London, pp 149–168. https://doi.org/10.2475/ajs.274.4.321
Miyashiro A (1974) Volcanic rock series in Island arcs and active continental margins. Am J Sci 274:321–355. https://doi.org/10.2475/ajs.274.4.321
Mori T, Burton M (2006) The SO_2 camera: a simple, fast and cheap method for ground-based imaging of SO_2 in volcanic plumes. Geophys Res Lett 33:L24804. https://doi.org/10.1029/2006GL027916
Moussallam Y, Peters N, Masias P, Aaza F, Barnie T, Schipper CI, Curtis A, Tamburello G, Aiuppa A, Bani P, Giudice G, Pieri D, Davies AG, Oppenheimer C (2017) Magmatic gas percolation through the old lava dome of El Misti volcano. Bull Volcanol 79:46. https://doi.org/10.1007/s00445-017-1129-5
Mulyadi E (1992) Le complexe de Bromo-Tengger (Est Java, Indonesie): Etude structurale et volcanologique. Univ. Blaise Pascal, Clermont-Ferrand, pp 1–152
Platt U, Stutz J (2008) Differential optical absorption spectroscopy, principles and applications. Springer, Cham, p 597
Rogers N (2015) The composition and origin of magmas. In: Sigurdsson H, Houghton B, Nutt SR, Rymer H, Stix J (eds) The encyclopedia of volcanoes, 2nd edn. Academic Press, San Diego, pp 93–112
Santoso NA, Bijaksana S, Kodama K, Santoso D, Dahrin D (2017) Multimethod approach to the study of recent volcanic ashes from Tengger Volcanic Complex, Eastern Java, Indonesia. Geosciences 7:63. https://doi.org/10.3390/geosciences7030063
Schiano P, Bourdon B, Clocchiatti R, Massare D, Varela ME, Bottinga Y (1998) Low-degree partial melting trends recorded in upper mantle minerals. Earth Planet Sci Lett 160:537–550. https://doi.org/10.1016/S0012-821X(98)00109-5
Shinohara H (2005) A new technique to estimate volcanic gas composition: plume measurements with a portable multi-sensor system. J Volcanol Geotherm Res 143:319–333. https://doi.org/10.1016/j.jvolgeores.2004.12.004
Shinohara H (2013) Volatile flux from subduction zone volcanoes: insights from a detailed evaluation of the fluxes from volcanoes in Japan. J Volcanol Geotherm Res 268:46–63. https://doi.org/10.1016/j.jvolgeores.2013.10.007
Smekens JF, Clarke AB, Burton MR, Harijoko A, Wibowo HE (2015) SO_2 emissions at Semeru volcano, Indonesia: characterization and quantification of persistent and periodic explosive activity. J Volcanol Geotherm Res 300:121–128. https://doi.org/10.1016/j.jvolgeores.2015.01.006
Tamburello G (2015) Ratiocalc: software for processing data from multicomponent volcanic gas analyzers. Comput Geosci 82:63–67. https://doi.org/10.1016/j.cageo.2015.05.004
Tamburello G, Kantzas EP, McGonigle AJS, Aiuppa A, Giudice G (2011) UV camera measurements of fumarole field degassing (La Fossa crater, Vulcano Island). J Volcanol Geotherm Res 199(1–2):45–52. https://doi.org/10.1016/j.jvolgeores.2010.10.004
Van Gerven M, Pichler H (1995) Some aspects of volcanology and geochemistry of Tengger Caldera, Java, Indonesia: eruption of a K-rich tholeiitic series. J Southest Asia Earth Sci 11(2):125–133. https://doi.org/10.1016/0743-9547(95)00003-B
Voigt S, Orphal J, Bogumil K, Burrows JP (2001) The temperature dependence (203–293 K) of the absorption cross-sections of O_3 in the 230–850 nm region measured by Fourier-transform spectroscopy. J Photochem Photobiol A 143(1):1–9. https://doi.org/10.1016/S1010-6030(01)00480-4
Whitford DJ, Nicholls IA, Taylor SR (1979) Spatial variations in the geochemistry of quaternary lavas across the Sunda Arc in Java and Bali. Contrib Mineral Petrol 70:341–356
Zaennudin A (1990) The stratocone of Mt Cemara Lawang Indonesia. Victoria University of Willington, pp 1–238

Publisher's Note