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# First determination of magma-derived gas emissions from Bromo volcano, eastern Java (Indonesia)

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ABSTRACT

The composition and fluxes of volcanic gases released by persistent open-vent degassing at Bromo Volcano, east Java (Indonesia), were characterised in September 2014 from both in-situ Multi-GAS analysis and remote spectroscopic (dual UV camera) measurements of volcanic plume emissions. Our results demonstrate that Bromo volcanic gas is water-rich ($H_2O/SO_2$ ratios of 56–160) and has $CO_2/SO_2$ ($4.1 \pm 0.7$) and $CO_2/S_{tot}$ ($3.2 \pm 0.7$) ratios within the compositional range of other high-temperature magma-derived gases in Indonesia. $H_2/H_2O$ and $H_2S/SO_2$ ratios constrain a magmatic gas source with minimal temperature of ~700 °C and oxygen fugacity of $10^{-17}$–$10^{-18}$ bars. UV camera sensing on September 20 and 21, 2014 indicates a steady daily mean $SO_2$ output of $166 \pm 38$ t d$^{-1}$, which is ten times higher than reported from few previous studies. Our results indicate that Bromo ranks amongst the strongest sources of quiescent volcanic $SO_2$ emission measured to date in Indonesia, being comparable to Merapi volcano in central Java. By combining our results for the gas composition with the $SO_2$ plume flux, we assess for the first time the fluxes of $H_2O$ ($4725 \pm 2292$ t d$^{-1}$), $CO_2$ ($466 \pm 83$ t d$^{-1}$), $H_2S$ ($25 \pm 12$ t d$^{-1}$) and $H_2$ ($1.1 \pm 0.8$) from Bromo. Our study thus contributes a new piece of information to the still limited data base for volcanic gas emissions in Indonesia, and confirms that much remain to be done to fully assess the contribution of this very active arc region to global volcanic gas fluxes.



## 1. Introduction

The Indonesian volcanic arc, extending from west Sumatra to Sulawesi in the northeast, hosts 140 identified active volcanoes (Global Volcanism Program, http://www.volcano.si.edu/), ~100 of which have erupted in the recent history (Simkin and Siebert, 1994). Indonesia is one of the most active volcanic regions on our planet, and paid a prominent tribute to the historical death toll from volcanism. Paradoxically, however, relatively little is known about the contribution of the Indonesian island arc to the global volcanic gas fluxes to the atmosphere (see Oppenheimer et al., 2014). In their reference compilation of volcanic $SO_2$ fluxes, Andres and Kasgnoc (1998) reported data for only 4 continuously degassing volcanoes in Indonesia (Merapi, Galunggung, Bromo and Slamet), whose single cumulative contribution (~0.1 Tg yr$^{-1}$) cannot account for the overall country's contribution to the global volcanic $SO_2$ budget (recently estimated as 10-18 Tg/yr by different authors; see Oppenheimer et al., 2014 for a review). Attempts to extrapolate from these few available data have led to estimates of a regional $SO_2$ flux that span more than one order of magnitude, from 0.12–0.18 Tg/yr (Hilton et al., 2002) to 3.5 Tg/yr (Nho et al., 1996). The latter figure also includes the contribution of eruptive degassing to the $SO_2$ budget. Syn-eruptive emissions in Indonesia were determined for only a few events, from either space-borne sensing or the petrologic method (see Pfeffer, 2007, for an updated list), but the total (passive + eruptive) $SO_2$ budget does not results better constrained (0.48–3.8 Tg/yr; Pfeffer, 2007) than that for only passive emissions. This paucity of information has persisted until today (see Shinohara, 2013), even though a recent work by Bani et al. (2013) provided the first $SO_2$ flux datum for Papandayan and further data for Bromo volcanoes in Java.

Our current knowledge for volcanic degassing in Indonesia is even more lacking for other major volcanic gas species such as $H_2O$ and $CO_2$, whose emission rates were quantified at only one single volcano, Merapi in central Java (Allard et al., 1995, 2011; Toutain et al., 2009). Published volcanic gas analyses are available for only ~10 Indonesian volcanoes (compiled in Pfeffer, 2007), which makes quantifying regional gas flux inventories very problematic. For instance, Hilton et al. (2002) estimated an Indonesian $CO_2$ flux of ~0.36 Tg/yr that is poorly

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constrained from very few data. In summary, given the intense volcanic activity in Indonesia and the important gas emissions sustained by other arc segments in the southwest Pacific, such as Papua New Guinea (McGonigle et al., 2004; McCormick et al., 2012) and Vanuatu (Bani et al., 2012), increasing the data base for volcanic gas compositions and fluxes in Indonesia is essential to refining current global volcanic gas inventories (Hilton et al., 2002; Burton et al., 2013; Shinohara, 2013).

Bromo volcano, a small pyroclastic cone inside the wide Tengger Caldera in eastern Java (Fig. 1), has been one of the most active volcanoes of Indonesia in historical time (GVP), displaying persistent plume emissions via open-vent degassing from its summit crater (Fig. 1c) and occasional eruptions (the last one in January-March 2011; GVP, 2012). This volcano has been studied on a few rare occasions from the ground for its $SO_2$ emission and considered to be a small emitter (Andres and Kasgnoc, 1998; Bani et al., 2013). However, satellite records in 2011–2013 have revealed that Bromo, in tandem with nearby Semeru volcano (Fig. 1d), ranks in the top-20 list of degassing volcanoes on Earth (Carn et al., 2014). Therefore, further ground-truth information is badly needed for better assessing its actual $SO_2$ flux contribution, but also the composition of its volcanic gases which have never been studied. This was the aim of our present work.

We here report on the results of a field survey performed in September 2014, during which the chemical composition of Bromo's volcanic gas plume was characterised using a Multi-component Gas Analyser System (Multi-GAS; Aiuppa et al., 2005; Shinohara, 2005). The volcanic $SO_2$ flux was also simultaneously determined using a dual-UV camera system (Tamburello et al., 2012). Combining the two data types allows us to provide the volatile emission budget for $H_2O$, $CO_2$, $SO_2$, $H_2S$ and $H_2$ from Bromo volcano.

## 2. Bromo volcano

Bromo (Latitude 7.942°S; Longitude 112.95°E) is a small tuff cone located in the central part of the Tengger caldera, a large (16-km-wide) polygenetic depression topping the summit of the (820 kyr old) Tengger volcanic massif in east Java (van Gerven and Pichler, 1995) (Fig. 1a–b). Bromo is the only active centre of a cluster of post-caldera

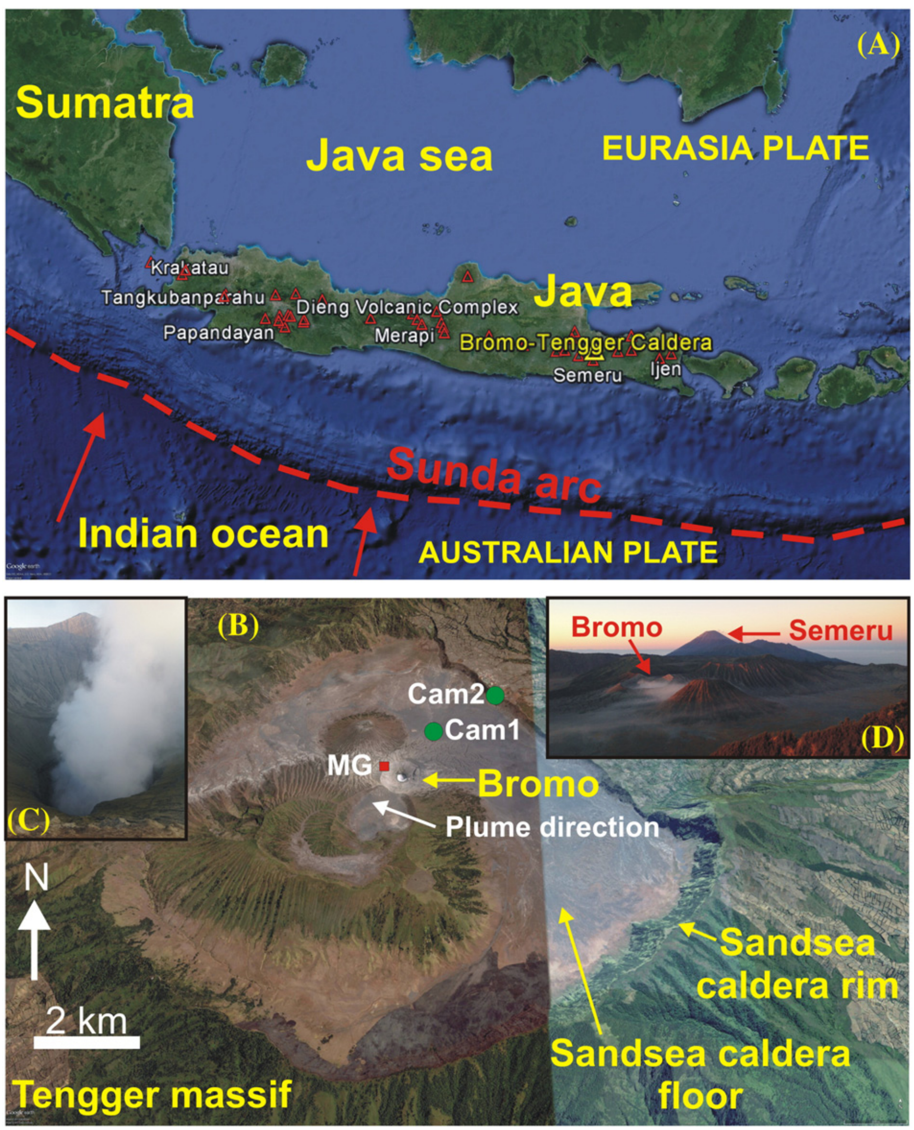


**Fig. 1.** (A) Map of Java island (source: Googleearthpro), showing the location of the most active Indonesian volcanoes (source: GVP) and of Bromo volcano on east Java. Volcanism in Java is related to subduction of the Australian Plate underneath the Eurasia Plate along the Sunda arc (the main direction of plate convergence is shown by red arrows); (B) Googleearthpro map of the Tengger caldera summit, showing the location of Bromo volcano. The red square (MG) indicates the position of the Multi-GAS, while the green circles stand for the positions of the UV camera on 20 September (Cam1) and 21 September (Cam2). Insets (C) and (D) are photos showing open-vent activity on Bromo's summit and a sunrise view of Bromo and Semeru volcanoes in the Tengger caldera, respectively.