Insights on hydrothermal-magmatic interactions and eruptive processes at Poás volcano (Costa Rica) from high-frequency gas monitoring and drone measurements

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Key Points:

- Three eruptive phases are characterized in detail through five years of high-frequency monitoring
- Precursors to phreatic and phreatomagmatic eruptions are identified and discussed
- Enhanced hydrothermal sealing can lead to larger eruptions and top-down remobilization of magma

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Abstract

Identification of unambiguous signals of volcanic unrest is crucial in hazard assessment. Processes leading to phreatic and phreatomagmatic eruptions remain poorly understood, inhibiting effective eruption forecasting. Our five-year gas record from Poás volcano, combined with geophysical data, reveals systematic behavior associated with hydrothermal-magmatic eruptions. Three eruptive episodes are covered, each with distinct geochemical and geophysical characteristics. Periods with larger eruptions tend to be associated with stronger excursions in monitoring data, particularly in SO_2/CO_2 and SO_2 flux. The explosive 2017 phreatomagmatic eruption was the largest eruption at Poás since 1953 and was preceded by dramatic changes in gas and geophysical parameters. The use of drones played a crucial role in gas monitoring during this eruptive period. Hydrothermal sealing and volatile accumulation, followed by top-down reactivation of a shallow previously-emplaced magma body upon seal failure, are proposed as important processes leading to and contributing to the explosivity of the 2017 eruption.

1 Introduction

Phreatic eruptions are common occurrences at wet volcanoes. Key questions regarding volcanic hazard assessment of these events are the role of magma, and whether they are precursors to larger magmatic eruptions [e.g. *Barberi et al.*, 1992; *Rouwet et al.*, 2014; *Stix and de Moor*, 2018]. Part of the problem in understanding and predicting eruptions involving magmatic and hydrothermal interactions is the diversity of potential processes in operation, including magma intrusion (e.g. Mt. St Helens 1980 eruption [*Cashman and Hoblitt*, 2004] and Ontake volcano 2007 eruption [*Nakamichi et al.*, 2009]), injection of magmatic gas into the hydrothermal system (e.g. White Island 2012 eruption [*Christenson et al.*, 2017], Poas 2014 [de Moor et al., 2016b])], hydrothermal sealing [e.g. Ruapehu 2007; *Christenson et al.*, 2010], infiltration of meteoric water [e.g. Mt St Helens

1989-1991; *Mastin*, 1994], and hydrothermal system response to earth tides [*Girona et al.*, 2018]. Detailed multi-disciplinary study of these systems is needed to better understand the processes and inform hazard assessment.

Poás volcano (N10.1977 W84.2310) is one of the most active volcanoes in Central America and is one of the best places in the world to study phreatic eruptions and dynamic interactions between magmatic gases and hydrothermal fluids. The crater typically hosts a warm hyper-acid lake (pH < 1, ~50˚C) [*Rowe et al.*, 1992; *Martinez et al.*, 2000], which frequently produces small phreatic eruptions. In April 2017 the volcano produced larger VEI 2 phreatic to phreatomagmatic eruptions, the most significant activity since 1955 (Fig S1) [*Salvage et al.*, 2018]. Poás was visited by ~500,000 tourists per year (before the latest eruption) and is located just 22 km north of the heavily-populated Central Valley (~3.5 million people) and SJO international airport. The acid lake is the shallow manifestation of an extensive hydrothermal system fed by magmatic gases [*Rowe et al.*, 1992]. Pools of liquid S were observed on the floor of the dessicated lake in the late 1980's [*Oppenheimer and Stevenson*, 1989], a phenomenon also observed in 2017 (Fig S1). Phreatic eruptions occur through the lake and are associated with increasing SO_2/CO_2, indicating that inputs of magmatic gas play a crucial role in these eruptions [*de Moor et al.*, 2016b].

The present study covers the period 2013 to present, focusing on the post-2014 activity and longer-term trends, based on MultiGAS measurements, SO_2 fluxes, seismicity, and deformation. We emphasize the precursors observed prior to the 2017 eruption and propose that hydrothermal sealing played an important role in priming the system (2015-2016) for the larger explosive eruptions (2017) when magmatic activity increased.

2 Eruptive activity

The current period of activity at Poás began in 2006 [*Rymer et al.*, 2009]. Three phases of eruptions are identified since 2012 (Fig 1). Phase 1 (2012 to 27 August 2014) produced numerous (~150) phreatic eruptions (columns ≤700m) through the lake. Phase 2 (5 June 2016 – 17 September 2016) produced ~80 phreatic eruptions, with column heights ≤400m. Phase 1 and 2 eruptions were similar, consisting of explosive expulsion of lake water, sediments, and altered bombs in cypresoidal columns accompanied by radial steam-rich base surges. Phase 3 (12 April 2017-24 September 2017) produced steam-rich eruption columns to ~4km (Fig S1b) and culminated in the first significant expulsion of magma at Poás since 1953-1955 [*Salvage et al.*, 2018].

Observations of the unrest preceding the 2017 eruption are insightful. On 1 April a geyser-like manifestation (locally termed "borbollón") emerged producing continuous jetting (up to ~20m) of sediment-rich water and steam at the edge of the lake. On 7 April an additional borbollón emerged on the crater floor, producing spouts up to 5m. The national park was closed on 9 April due to strong degassing (~400 T/d SO_2).

A small phreatic/phreatomagmatic explosion (<1km) occurred at 8pm on 12 April. The volcano produced a similar-sized eruption on 13 April at 3:45 pm. On 14 April at 7:57am a column of ~4km was observed, with bombs impacting the tourist overlook. A ~40m-wide crater was formed and flooded by lake water. Small eruptions were frequent, until 22 April when a strong phreatomagmatic eruption occurred, ejecting large plastic breadcrust bombs around the vent (Fig S1c). Inspection of erupted material indicated that the early eruptive products were dominated by hydrothermally altered material whereas later products were dominated by fresh-looking glassy clasts.

The new vent erupted semi-continuously from late April through September 2017, forming a tuff cone that occasionally inhibited the influx of crater lake water. The porous

dam failed and reformed on numerous occasions. The gas and ash plume was often visibly water-rich (dense white eruption column ejected through the lake). The dessication of the crater lake in mid-June (Fig 1) revealed a canary-yellow cone of native sulfur (S; Fig S1d) and a dark grey pool of molten native S. After disappearance of the lake, ash emissions appeared drier (Fig S1e) and gradually decreased in frequency until the end of phase 3 eruptive activity in late September 2018.

3 Methods

Sulfur dioxide (SO_2) flux has been monitored at Poás since 2013 (Fig 1) following the walking traverse method of de Moor et al. [2016b]. During the 2017 eruptive crisis drones were used to determine SO_2 flux (Section S2; Figs S2 and S3). In June 2017 two scanning DOAS instruments [*Galle et al.*, 2010] were installed downwind of the volcano (Section S3).

Key gas ratios (SO_2/CO_2 and H_2S/SO_2) are monitored via a permanent multiple gas analyzer (MultiGAS) [*Aiuppa et al.*, 2005; *Shinohara*, 2005] located on the western rim of the crater (Section S1; Fig S2). Gas ratios are calculated in real time and telemetered via radio. The prior MultiGAS station located in the crater was destroyed on 13 April 2017 by a climactic eruption. Thereafter, drones were used for measurements of gas ratios (Section S2, Fig S3). A permanent MultiGAS was installed again once eruptive activity had diminished in November 2017. Details of the seismic and GPS networks and methods are available in Salvage et al. [2018].

4 Results

The dynamic nature of degassing at Poás is evident through the 5-year dataset (Fig 1). SO_2 fluxes have varied from below detection limit to ~3000 T/d. SO_2/CO_2 ratios have varied over 3 orders of magnitude, from <0.03 to >30 and H_2S/SO_2 has varied from <0.01 to ~4. Though there is no obvious relationship between lake and fumarole temperatures, their

respective gas compositions track each other over time, consistent with changes in a common source and minimal scrubbing by the hyper-acid lake [*de Moor et al.*, 2016b]. This article considers major changes affecting the gas emissions of the bulk system.

Eruptive phase 1 was characterized by moderate SO_2 flux (70T/d to 220T/d, average of 130T/d). SO_2/CO_2 ratios were high at both the dome fumaroles and the lake gas emissions. H_2S/SO_2 was low during this period. High-frequency changes in SO_2/CO_2 in lake gas emissions were correlated with individual phreatic eruptions [*de Moor et al.*, 2016b]. Long period (LP) seismicity was relatively high during phase 1 with on average 227 LP events observed per day. Volcano tectonic (VT) seismicity was low with less than 1 event/day observed.

Eruptive phase 1 was followed by almost 2 years of repose with no phreatic activity. The SO_2 flux declined gradually, reaching values ~30 T/d in late 2015. SO_2/CO_2 also decreased and H_2S became more prevalent. LP seismicity decreased to an average of 18 events/day in 2016. A GPS station was installed in late 2014 and showed oscillations in vertical displacement with an amplitude of ~2cm with a mild overall inflation noted through the end of phase 2 eruptions.

A brief period of phreatic eruptions occurred in June to September 2016 (phase 2), accompanied by a pronounced SO_2/CO_2 peak about 1 month after the onset of eruptions, wherein values increased from 0.06 to 0.7 and then decreased to 0.03. LP seismicity demonstrated an increase in the two weeks prior to the onset of phase 2, with 112 events observed per day, a significant escalation over the average for the preceding repose period. Vertical displacement and VT counts did not show a significant change.

The subsequent repose period was notable due to the very low SO_2 flux (< 20 T/d; Fig 1) and high H_2S/SO_2. SO_2/CO_2 ratios were exceptionally low, at values less than 0.04. LP seismicity was also low, with on average 1 event/day between the end of phase 2 and the

beginning of 2017. A clear change in SO_2/CO_2 trend occurred in November 2016, from negative to positive slope, perhaps an early indicator that the probability of eruption was increasing. The change in SO_2/CO_2 slope was associated with a mild deflation event in late 2016 and early 2017. Long period seismicity increased significantly in February-March 2017 (127 events/day on average), likely a result of fluid movement and over-pressuring of the system [*Salvage et al.*, 2018].

Dramatic changes in gas emissions, seismicity, and vertical displacement were observed prior to the phase 3 climactic eruptions. H_2S/SO_2 plummeted from an average of 2.4 for March to <0.01 on 31 March (Fig 1d). SO_2/CO_2 increased from ~0.04 for March to 0.10 on 30 March and 0.44 on 1 April i.e. an increase of an order of magnitude in 4 days (Fig 1 inset). These major changes were observed in both lake and fumarole gases. SO_2/CO_2 continued to increase exponentially until the eruption on 13 April, which destroyed the permanent MultiGAS station. The average SO_2/CO_2 value increased by 2 to 3 orders of magnitude in 2 weeks, at that time the largest change recorded since 2014. Though SO_2 flux data are sparse during the 5-month runup to phase 3 due to barely detectable SO_2 emissions, the existing data show that the dramatic change in SO_2/CO_2 was paralleled by an equally dramatic increase in SO_2 flux, from <20 T/day on 28 March 2017 to 1510±290 T/day on 13 April 2017. The similarity in the magnitude and timing of the variations in SO_2/CO_2 and SO_2 flux suggest that these parameters are related (Fig 2a), although the SO_2 flux measurements suffer from relative data sparsity and detection limits that inhibit assessment of subtle changes in the run-up to phase 3 (Fig 1).

Details of the seismic behavior associated with the 2017 eruption are published in Salvage et al. [2018]. To summarize, LP seismic activity peaked during the evolving crisis, reaching levels comparable to phase 1 eruptive activity in late March 2018 (Fig 1e). Notably 704 LP events were recorded on 5 April 2017 and 776 events were recorded on 22 April

2017, the latter associated with the expulsion of magmatic bombs. VT events also increased before the onset of phase 3, with ~ 4 events/day in the two weeks prior. Many of these precursory VT events were located close to the surface, though the sparsity of seismic station precludes accurate location. The later phase 3 eruptive period was notable in terms of VT seismicity, which peaked in May-July 2017. Deformation showed inflation to 1.7 cm above background by 12 April and 3.3 cm of inflation by 20 April.

Drone flights on 10 May 2017 revealed exceptionally high average SO_2/CO_2 of 33.3 ± 11.0 (n=4 with range of 21.9 to 48.7). By late May SO_2/CO_2 had dropped to 3-10. The post-eruptive period was associated with SO_2/CO_2 values of 0.5- 3. The lake reappeared in January 2018, and was marked by a gradual decrease in SO_2/CO_2 to < 0.3 and a decrease in SO_2 flux, presumably due to scrubbing in response to meteoric water influx. A change in SO_2/CO_2 trend occurred in early March 2018, associated with dessication of the lake. A correlation is observed between daily SO_2/CO_2 measured by MultiGAS and SO_2 flux measured by DOAS (Fig. 2a), suggesting that S chemistry in hydrothermal fluids and/or in magmas is driving the major observed variations.

5 Discussion

High-frequency monitoring of the 2017 phreatomagmatic eruption at Poás provides insight into eruptive triggering at hydrothermal-magmatic volcanoes. Four observations are striking (Fig 1): 1. The decrease in SO_2 flux in the two years prior to the eruption, 2. the large change in all monitored parameters immediately prior to the eruption, especially the precipitous drop in H_2S/SO_2 and the parallel increases in SO_2 flux and SO_2/CO_2 (Fig 2a) 3. the associated high SO_2/CO_2 ratios and VT seismicity after the initiation of the eruption (Fig1), and 4. the subdued increase in CO_2 flux after the initiation of the eruption in combination with elevated vertical displacement in the post eruptive period. We consider

two conceptual models to explain these observations. The first proposes injection of new magma as the cause of eruption. The second scenario considers hydrothermal sealing as the responsible process, through accumulation of volatiles and overpressure, ultimately leading to seal failure and eruption. Finally, we propose that these models are not mutually exclusive.

5.1 Magma intrusion as the eruption driver

The 2017 eruption was the first expulsion of magma at Poás since 1953-1955. The increasing juvenile component of ash through the initial phases of the eruption (Fig S5) and the ejection of large plastic breadcrust bombs on 22 April 2017 (Fig S1) clearly demonstrate the involvement of magma in the eruption. Thus, an obvious primary consideration would be that injection of magma drove the eruption. However, juvenile bombs from the eruption are andesitic in composition – more evolved than the basaltic magma erupted in 1953-1955 (Table S2). This may suggest that a different part of the magma reservoir was mobilized during the 2017 eruption, or that a basaltic intrusion into the deeper system triggered eruption of overlying andesite [e.g. *Pallister et al.,* 1992; *Murphy et al.,* 2000].

Gas ratios (SO_2/CO_2 and H_2S/SO_2) and SO_2 flux during the eruption suggest a very shallow magmatic source. Following the solubility degassing model of de Moor et al. [2016a] for a S-rich and CO_2-poor mafic magma typical of Costa Rican volcanoes, SO_2/CO_2 values greater than 5 require equilibrium with melt at <15MPa, indicating a shallow magma source at <500m. SO_2/CO_2 values as high as ~15 can be explained by magmatic degassing at ambient pressure. Carbon dioxide is less soluble than SO_2, therefore magmatic contribution from deeper sources would drive the SO_2/CO_2 ratio down by mixing with CO_2-rich gases. Thus, the very high SO_2/CO_2 values associated with the 2017 eruption indicate that deep magma was not involved. Rather, the gas data suggest that the source was partially degassed magma previously emplaced to shallow levels (probably in late 2000 [*Fischer et al*., 2015] to

≥500m depth [*Rymer et al.*, 2009]), which is in also consistent with the more evolved composition of the 2017 magma. The total amount of SO_2 emitted during the eruption (~440 kT) and the average SO_2/CO_2 measured during eruptive phase 3 (4. 9) can be explained by a gas phase derived from ~0.1 km^3 of partially degassed magma with ~800 ppm residual S and less than 1% of its original CO_2 (Section S4). No prior pulse of CO_2–rich magmatic gas was observed, as has been seen for example at Etna [*Aiuppa et al.*, 2007], Redoubt [*Werner et al.*, 2013], Turrialba [*de Moor et al.*, 2016a], and Masaya [*Aiuppa et al.*, 2018]. This seems to rule out intrusion of deeper basaltic magma as the eruption trigger.

Geophysical data provide further insight into the role of magma. Vertical displacement remains elevated after the eruption, indicating that a significant increase in subsurface volume occurred, likely associated with movement of magma to shallower levels [e.g. *Dzurisin*, 2003]. The VT seismicity associated with the eruption [*Salvage et al*., 2018] is also consistent with magma intrusion causing changes in stress fields or propagation of pore fluid pressure leading to slip on local faults [e.g. *Roman and Cashman*, 2006; *White and McCausland*, 2016]. In summary, there is no doubt that magma was involved in the 2017 eruption. Geophysical data demonstrate that magma was emplaced to shallow levels, and gas data further elucidate a shallow magmatic source for the volatiles.

5.2 Failure of the hydrothermal seal as an eruption trigger

A crucial consideration in assessing the processes driving the phase 3 activity is the pre-eruptive condition of the system. It is conceivable, given the lack of evidence for intrusion of CO_2-rich basaltic magma from depth, that a top-down eruption triggering mechanism also played an important role. Particularly, the gas data show evidence for hydrothermal sealing in the two years prior to the 2017 eruption.

The prolonged period of pre-eruptive decrease in SO_2 flux combined with low SO_2/CO_2 and high H_2S/SO_2 indicate hydrothermal S deposition processes [*Giggenbach*, 1996; *Symonds et al.*, 2001; *de Moor et al.*, 2016b]. Based on the decrease in SO_2 flux below background levels (roughly 150T/d SO_2 equivalent, including H_2S emissions, and based on 2009 to 2014 data), we calculate that the S deposition rate in 2016 and early 2017 was ~14,000 m^3/yr of elemental S. This value is an order of magnitude higher than the rate calculated by Rowe et al. [1992] for Poás, suggesting that hydrothermal sealing was taking place at a significantly enhanced rate in 2015-2017 (interestingly, the eruptive cycle of the 1980s studied by Rowe et al. [1992] did not culminate in magma extrusion). As described by Christensen et al. [2010], hydrothermal sealing can lead to decreased vent porosity and permeability, pressurization, and phreatic eruptions that can entrain shallow magma. In our dataset, the dominance of H_2S over SO_2 in the period between phase 2 and phase 3 eruptions is powerful evidence of strong hydrothermal processes [e.g. *Giggenbach*, 1996] leading up to the 2017 eruption. Indeed, the rapid switch from H_2S-dominated to SO_2-dominated gases in late March 2017 was a clear sign that the system was unstable and that magmatic fluids were reaching the surface. The parallel behavior of SO_2/CO_2 and SO_2 flux (Fig 2a) further indicates that S chemistry plays a fundamentally important role in dynamic behavior at Poás and the variations in gas monitoring parameters.

Fig 2b presents a model of hydrothermal seal formation at Poás (Section S5). High T magmatic gases cool while rising through a basaltic andesite conduit. Sulfur starts precipitating at ~215˚C S, with 50% of the total SO_2 gas deposited as elemental S over a narrow temperature decrease of 25˚C [calculated using data from *Rodríguez and van Bergen*, 2017]. Once the gas cools to100˚C, 96% of its S is deposited. Based on the decreased SO_2 flux, we calculate that this process filled ~40m^3 of pore space per day. The steam component of the gas condenses and secondary minerals form from reaction of this acidic liquid with

wall rock. The resulting hydrated mineral assemblage is silica + kaolinite + illite + hematite + anatase + pyrite + K-alunite [*Rodríguez and van Bergen*, 2017], which is about 10% less dense than the unaltered basaltic andesite. Thus, *in situ* rock alteration results in expansion that contributes to the sealing process. Considering gas cooling and condensate reaction with rock, the total sealing capacity for the pre-2017 eruption period is calculated at ~50 m^3/day (Fig 2b). The total volume of pore-filling secondary mineralization during the period of hydrothermal sealing (5/2015 to 3/2017) is calculated at ~24,000 m^3. Considering substrate porosity of ~20% [*Todesco et al.*, 2015], the sealed volume at Poás prior to the eruption was ~120,000 m^3 (volume of yellow cone in Fig 3), Here, it is important to note that filling of pore spaces is not expected to produce inflation as the subsurface volume does not change. Rather, the mild inflation observed between 2015 and phase 2 eruptions was more likely due to volatile accumulation below the seal, ultimately leading to its expulsion. The total modeled seal volume closely matches the volume of altered material erupted in the 2017 eruption (~122,000 m^3; Section S6), lending credence to our model approach.

Thus, there is strong evidence that a hydrothermal seal formed and was subsequently expelled during the opening phases of the 2017 eruption. The notable but brief increase in SO_2/CO_2 during small phase 2 eruptions is interpreted as a response of the system to sealing of the dome fumarole conduit, diverting emissions to the lake vents and driving small phreatic eruptions. This ephemeral excursion was superimposed on the longer trend of decreasing SO_2/CO_2 and increasing H_2S/SO_2 associated with sealing. The first evidence for rupture of the seal was suggested by a change in SO_2/CO_2 slope in November 2016, which was accompanied by deflation and followed by increasing LP seismicity after January 2017 (Fig 1; Salvage et al., 2018). It is notble that LP seismicity did not precede the change in SO_2/CO_2 slope. Rather, early escape of volatiles through the failing seal could have resulted in decompression boiling, generating LP events, disrupting the underlying hydrothermal-

magmatic system, and leading to catastrophic seal failure, and massive escape of magmatic volatiles (high SO_2 fluxes). Thus, a downward propagating depressurization through the hydrothermal-magmatic system triggered by hydrothermal seal failure is hypothesized as the trigger mechanism for the 2017 eruption at Poás.

5.3 Nuanced feedbacks between magmatic and hydrothermal processes

Magmatic gases feed hydrothermal systems, resulting in acid fluids that both dissolve rock to create porosity and precipitate secondary minerals to fill it [e.g. *Varekamp et al.*, 2001]. Magmatic heat, mostly transferred by upward migrating gases, drives vaporization of liquid water, leading to boiling pools, geyser-like exhalations, and small phreatic eruptions [*Rouwet and Morrissey*, 2015; *Stix and de Moor*, 2018]. Sealing plays a crucial role in accumulation of pressure and the generation of more explosive eruptions, which can perturb and remobilize shallowly emplaced magma [*Giggenbach et al.*, 1990; *Christenson et al.*, 2010; *Stix and de Moor*, 2018].

De Moor et al. [2016b] proposed a model for small phase 1 (2014) phreatic eruptions at Poás whereby transient pulses of magmatic gas and heat drive vaporization leading to eruption. These small oscillations in volatile injection could be related to either magmatic processes such as variations in magma supply rate or convection rate, or to opening and closing of a constriction in the magmatic or deeper hydrothermal plumbing system. Shallow hydrothermal sealing also undoubtedly plays a role in phreatic eruptions, as explosive activity requires pressure buildup in a confined space (decreased permeability) followed by energetic release when the tensile strength of the confining medium is exceeded. Small and frequent eruptions, epitomized by phase 1 activity at Poás, serve to increase permeability through fracturing, thus preventing large overpressures and promoting water influx into the conduit. In these small, geyser-like phreatic eruptions, vaporization of water by magmatic heat is thus

considered the distinguishing process over hydrothermal sealing [*Stix and de Moor*, 2018]. Enhanced hydrothermal sealing, as observed at Poás in the period leading up to the 2017 eruption, is more likely during decreased magmatic gas and heat input to the shallow system. Under these conditions, conduits can seal more efficiently because explosive fracturing (i.e. eruptions) in the conduit is absent. If magmatic gas input then resumes, greater pressurization occurs, leading to more explosive eruptions.

We speculate that variations in the fluid flux between magmatic and hydrothermal reservoirs are intricately related with hydrothermal processes acting to seal the system, as well as to the vaporization processes driving eruptions that open conduits. Subtle variations in magma supply rate or in magma convection in the lower regions of the plumbing system likely have consequences for the upper hydrothermal system, which could prime the system for more explosive eruptions. High frequency variations in magmatic input drive frequent small phreatic eruptions (phase 1), whereas longer frequency variations can lead to enhanced sealing and thus larger phreatic/vulcanian eruptions when input resumes.

6 Conclusions

The efficacy of incorporating high-frequency gas monitoring into more traditional geophysical volcano monitoring programs volcanoes is demonstrated by the 5-year record at Poás. Combining geophysical methods with gas monitoring can not only provide important precursors to eruptions (rapid increase in SO_2/CO_2 and SO_2 flux, combined with inflation and increased seismicity) but also identify pre-eruptive processes and conditions likely to promote more explosive eruptions (hydrothermal sealing implied by low gas emissions, high H_2S/SO_2 and subtle inflation). Formation and failure of hydrothermal seals is suggested as a fundamentally important process in generating larger phreatic to phreatomagmatic eruptions, and may result in top-down destabilization of hydrothermal-magmatic systems through

downward-propagating decompression. Phreatic explosions prior to magmatic eruptions are often considered a by-product of magma intrusion. However, in some cases hydrothermal processes may play a fundamental role in initiating magmatic eruptions. The processes driving phreatic to phreatomagmatic eruptions at Poás are likely operational at many volcanoes with shallow magma and strong hydrothermal systems.

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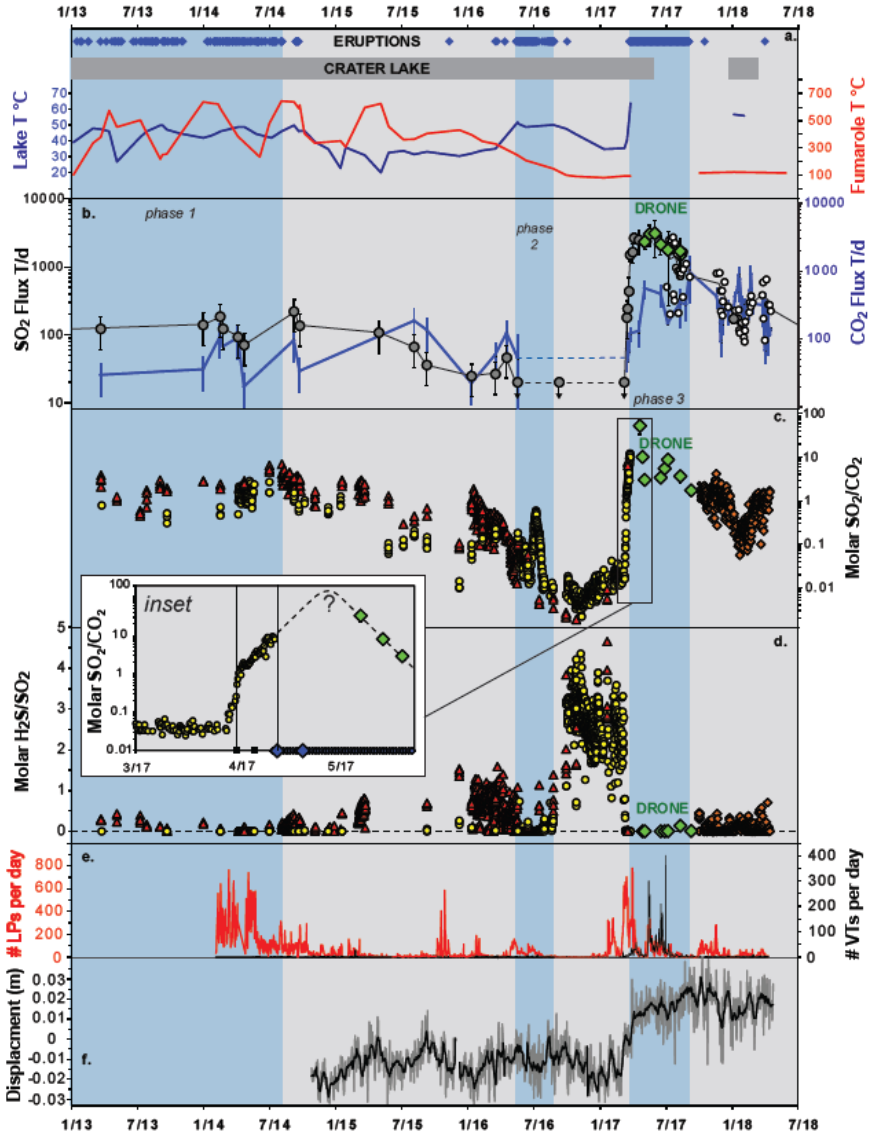

Figure 1. Time series of volcano monitoring data for Poás since 2013. Green diamonds show gas data acquired with drones in plots b-d. Panel a – occurrence of eruptions, presence of crater lake, and temperature data for lake and fumaroles. b. SO_2 flux (grey circles = traverses, white circles = scanning DOAS data. Blue line shows calculated CO_2 flux (from SO_2 flux and SO_2/CO_2), with dashed section indicating period where degassing was too low (<20 T/d SO_2) for robust flux measurements. c & d MultiGAS data (yellow circles = lake plume, red triangles = fumarole plume, orange diamonds = mixed plume post 2017 eruptions) e. Seismic activity showing long period (LPs, red) and volcano tectonic (VTs, black) counts per day f. GPS vertical displacement data. The three eruptive phases are shown as blue shading. Inset shows zoom of MultiGAS data in run-up to 2017 eruption, where black squares are "borbollón" events and blue diamonds are eruptions. Larger blue diamonds represent eruption columns ≥4km.

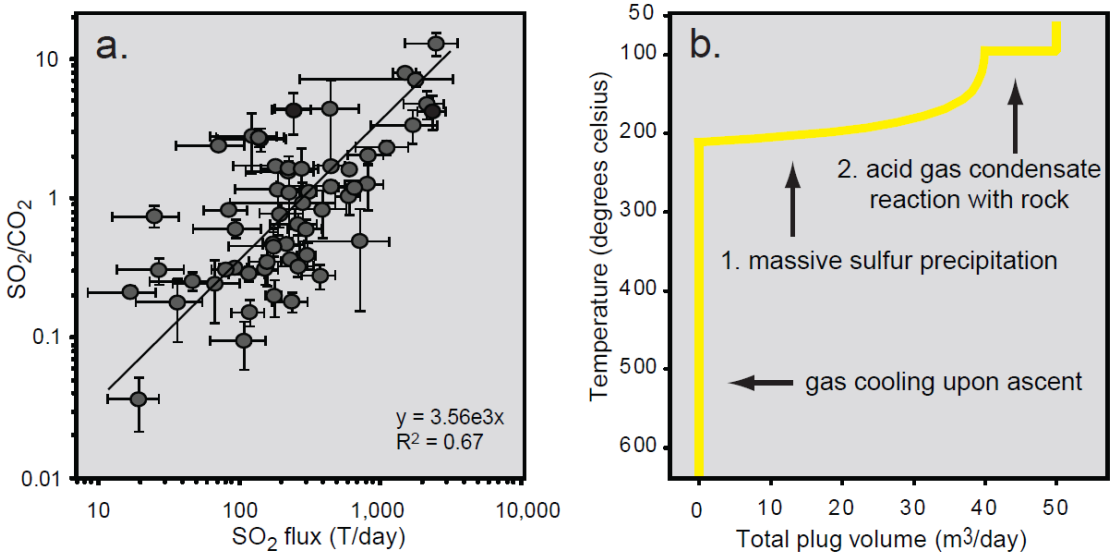

Figure 2. a Relationship between SO_2/CO_2 and SO_2 flux. Error bars represent 1σ standard deviation in daily averages, and two outliers (solid black symbols) were excluded from linear fit. **b** Model of hydrothermal sealing showing volume of plug formed per day, with magmatic gas input constrained by SO_2 fluxes.

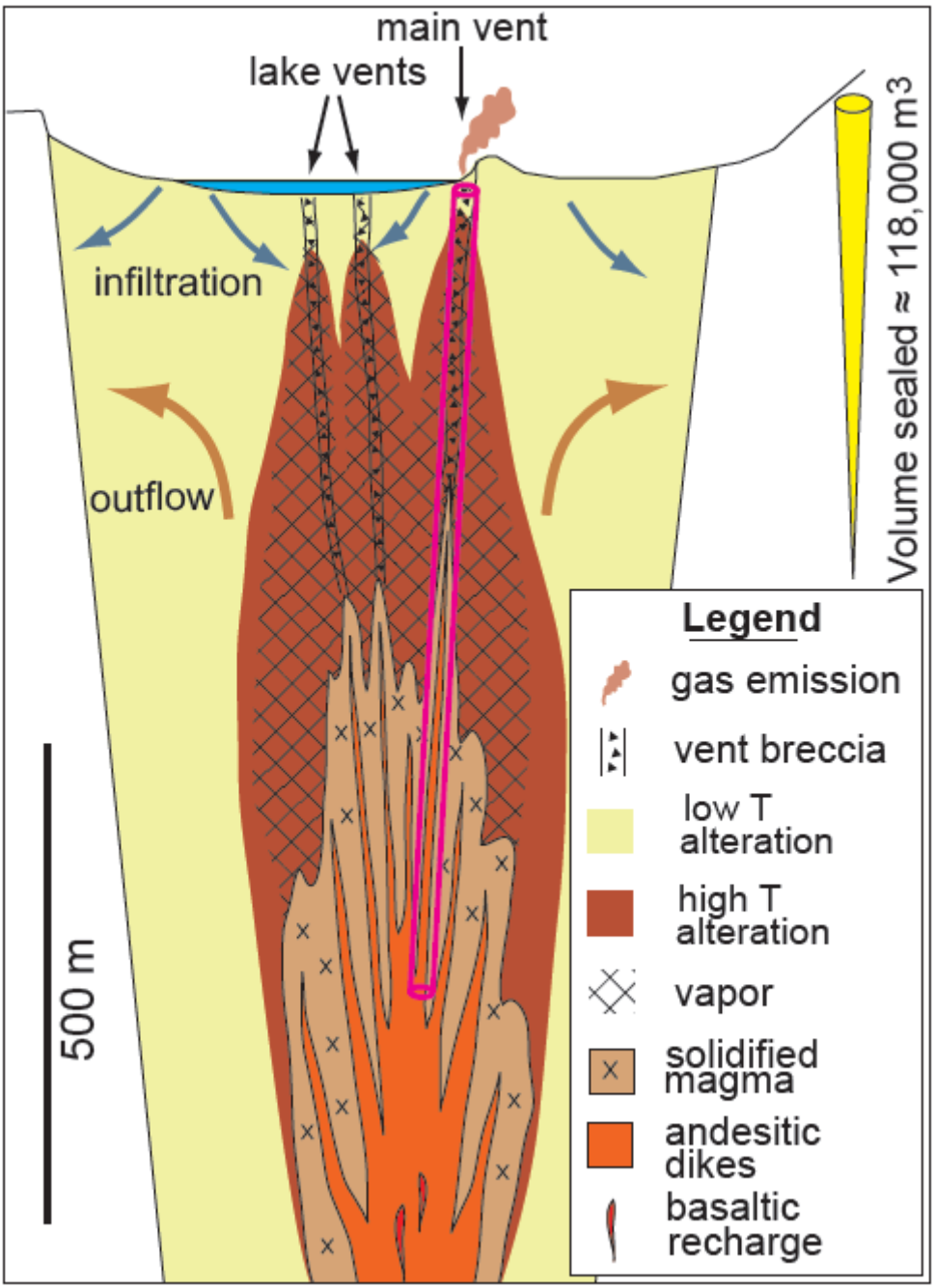

Figure 3. Schematic diagram (roughly to scale) of the Poás hydrothermal-magmatic system. Yellow cone = volume sealed prior to the 2017 eruption. Pink cylinder = approximate region of the system ejected by 2017 eruption. Prior to eruption, the upper conduits (shown as vent breccias) were sealed by hydrothermal mineralization in 2015-2017, leading to pressure accumulation in the vapor zone and more explosive behavior in phase 3 eruptions.