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Abstract

Space-based thermal data are increasingly used for monitoring effusive eruptions, especially for calculating lava discharge rates and forecasting hazards related to basaltic lava flows. The application of this methodology to silicic, more viscous lava bodies (such as obsidian lava flows) is much less frequent, with only few examples documented in the last decades. The 2011-2012 eruption of Cordón Caulle volcano (Chile) produced a voluminous obsidian lava flow (~ 0.6 km^3) and offers an exceptional opportunity to analyze the relationship between heat and volumetric flux for such type of viscous lava bodies. Based on a retrospective analysis of MODIS infrared data (MIROVA system), we found that the energy radiated by the active lava flow is robustly correlated with the erupted lava volume, measured independently. We found that after a transient time of about 15 days, the coefficient of proportionality between radiant and volumetric flux becomes almost steady, and stabilizes around a value of ~ 5×10^6 J m^{-3}. This coefficient (i.e. radiant density) is much lower than those found for basalts (~ 1×10^8 J m^{-3}) and likely reflects the appropriate spreading and cooling properties of the highly-insulated, viscous flows. The effusion rates trend inferred from MODIS data correlates well with the tremor amplitude and with the plume elevation recorded throughout the eruption, thus suggesting a link between the effusive and the coeval explosive activity. Modelling of the eruptive trend indicates that the Cordón Caulle eruption occurred in two stages, either incompletely draining a single magma reservoir or more probably tapping multiple interconnected magmatic compartments.

Keywords: effusion rates, obsidian lava flow, radiant power, Puyehue-Cordón Caulle, satellite thermal remote sensing

1. Introduction

The rate at which magma is erupted is a key parameter for understanding and modelling volcanic eruptions. When the magma is effused or extruded, the discharge rate that characterizes a given eruption reveals the pressure changes inside the magma chamber, and its modelling may constrain the location and capacity of magma storage zones (Wadge, 1981; Stasiuk et al., 1993; Melnik and Sparks, 1999). Lava discharge rates are essential for evaluating eruption dynamics (e.g. Harris et al., 2000), and represent one of the key parameter necessary to forecast lava flow paths and evaluate the associated hazards (e.g. Ganci et al., 2012; Harris et al., 2016).

During the past thirty years, several works focused on estimating lava discharge rates by using satellite thermal data (Harris, 2013 and reference therein). This approach, hereby called "thermal proxy", is essentially based on the relationships between heat and volumetric fluxes of active lava bodies (e.g. Pieri and Baloga, 1986; Harris et al., 1998; Wright et al., 2001; Harris et al., 2007; Dragoni and Tallarico, 2009; Harris and Baloga, 2009; Garel et al., 2012; Coppola et al., 2013; Harris et al., 2016). Notably, most of the literature has been focused on estimation of the effusion rates at basaltic volcanoes, such as Bardarbunga-Holuhraun (Coppola et al., 2017), Etna (Harris et al., 1998, 2011; Harris and Neri, 2002; Gouhier et al., 2012; Ganci et al., 2012), Kilauea (Koeppen et al., 2013), Hekla (Harris et al., 2000), Stromboli (Calvari et al., 2005, 2010; Valade et al., 2016; Zakŝek et al., 2015), Piton de la Fournaise (Coppola et al., 2009, 2017), Nyamulagira (Coppola and Cigolini, 2013; Coppola et al., 2016), Ambrym (Coppola et al., 2016), and Okmok (Patrick et al., 2003). In contrast, the number of studies drastically drops when considering viscous lavas bodies such as silicic flows (Harris et al., 2002, 2004) and domes (Harris and Ripepe, 2007; van Manen et al., 2010; Coppola et al., 2016). Studies are limited by a smaller number of eruptions characterized by felsic domes-flows emplacement, with respect to basaltic lava flows (Wright, 2016), but also by the complex relationships between eruption rate, heat balance, morphology and rheology that characterize the emplacement of viscous lava (e.g. Fink et al., 1998; Griffith, 2000; Harris and

Baloga, 2009). The reliability of the thermal approach as a universal method to estimate effusion rates over a broad spectrum of lava bodies, is still matter of debate (i.e. Dragoni and Tallarico, 2009; Garel et al., 2012). For example, Harris and Baloga (2009) stressed that the relationships between effusion rates, flow planar areas and radiant flux will vary between thermal, rheological, compositional and ambient (e.g. slope and flow bed roughness) conditions, so that a relationship developed for basaltic lavas cannot be directly applied to andesitic lavas or other higher in silica content. Moreover, recent laboratory and analytic models suggest that the relationship between radiated power and effusion rate becomes valid (i.e. stationary) only after a transient time, in which the lava flow reaches a thermal equilibrium (Garel et al., 2012, 2014). While for basaltic lava flow a transient time of hours to days is now in now well constrained from theory and observations, (Garel et al., 2012, 2014, Coppola et al., 2013), for silicic lava domes there is still a lack of measurements, with thermal modelling suggesting transient time of several years (Garel et al., 2012). The 2011-2012 rhyodacitic eruption of Cordón Caulle (CC) provides an exceptional training opportunity to test the thermal proxy over a voluminous (~ 0,6 km^3), long-lasting (~ 1 year) obsidian lava flow (Bertin et al., 2015).

In this paper, we used MODIS (Moderate Resolution Imaging Spectroradiometer) infrared data, automatically processed by the MIROVA (Middle Infrared Observation of Volcanic Activity) system (Coppola et al., 2016), to analyze and quantify the thermal output related to the Cordón Caulle eruption. Hence, we assess the reliability of the thermal proxy over silicic flows, by comparing the radiant energy emitted by the obsidian CC lava flow with independent and systematic measurements of lava flow volumes, derived from satellite-based topographic mapping (Bertin et al., 2015). The comparison of satellite-based effusive trend with other geophysical parameters is finally used to interpret the effusive process of CC eruption, in terms of magma discharge models.

2. Geological setting and chronology of the 2011-2012 Cordón Caulle eruption

2.1 Cordón Caulle Volcanic Complex

The Cordón Caulle Volcanic Complex (CCVC) is a 15 km NW-SE elongated corridor of eruptive centres located in the Southern Volcanic Zone (SVZ) of the Andes. This complex (Fig. 1a) is formed by the Cordón Caulle fissure system (CC), which connects the Pleistocene Cordillera Nevada caldera, at the NW tip, with the Puyehue stratovolcano, on SE (Lara et al., 2006a; Singer et al., 2008; Lara and Moreno, 2006). Tectonic setting of CCVC is characterised by the superimposition of the Quaternary tectonic regime (see Cembrano and Lara, 2009 for a review) over a pre-Andean NW striking structure (Lara et al., 2004). This results in complex interactions between the pathways of magmatic ascent system and the structural setting, especially along the Cordón Caulle fissure (Lara et al., 2004, 2006a, 2006b). Holocene eruptions evacuated rhyodacitic to rhyolitic magmas mostly from Cordón Caulle, whereas basaltic to andesitic lavas were erupted exclusively from Puyehue stratovolcano (Lara et al., 2004; Singer et al., 2008). In the latter century, Cordón Caulle showed a remarkable explosive and effusive activity, with the 1921-1922, the 1960 and the 2011-2012 eruptions characterised by the emission of large volumes (> 0.5 km^3 of tephra, comparable to lava volume) of silicic materials (up to 71 wt% in SiO_2; Castro et al., 2013) (cf. Singer et al., 2008; Jay et al., 2014). Earthquake-volcano mechanisms may be responsible for the triggering of the latter eruptions due to (i) the occurrence of high-magnitude, subduction-related seismic events prior the eruptive phases (Lara et al., 2004), or (ii) intra-arc tectonics (Wendt et al., 2017).

Figure 1

2.2 Chronology of the 2011 – 2012 eruption

The eruption of the Cordón Caulle began on 4 June 2011, following two months of increasing seismic activity below the CCVC (Silva-Parejas et al., 2012; Bertin et al., 2015; Elissondo et al., 2016). The first explosive stage was characterised by vigorous pyroclastic and gas-vent activity, with eruptive column reaching ~14 km during the first hours of the eruption (Castro et al., 2013). The ash plume rapidly reached the Atlantic coast affecting Buenos Aires and several Argentinean provinces (Collini et al., 2013, Pistolesi et al., 2015). During the 27 h climax phase, ~ 0.25 km^3 of rhyodacitic tephra was ejected, releasing about 0.2 Mt of sulphur dioxide (Silva-Parejas et al., 2012; Theys et al., 2013; Farquharson et al., 2015; Jay et al., 2014). Pulses of major explosive activity continued until the 15 June, with a mass flow rate constantly above 10^6 kg s^{-1}. However, a general decrease in the height of pyroclastic columns from 12 km to 8 km was observed in the following days (Bonadonna et al., 2015). On 15 June 2011, the extrusion of a viscous lava body began from the same vent. The effusive phase was characterised by an initial (~10 days) discharge rate up to 70 m^3 s^{-1} (Castro et al., 2013; Bertin et al., 2015), generating an extensive compound flow with structural and textural features typical of obsidian flows (Tuffen et al., 2013). The emplacement was characterised by significant flow inflation and the formation of several breakout lobes that gradually enlarged the flow field. Lava flow facies comprised rubbly, 'A'ā-like lava surface (30–45 m thick) as well as large coherent slabs, spines and tongues of lava (20 m thick), that were essentially localised along *en-échelon* tensional fractures and breakouts (Tuffen et al., 2013; Farquharson et al., 2015). Apparent viscosities of ~10^{10} Pa s were estimated on the basis of the eruption temperature (900°C; Castro et al., 2013) and the average advance rate of breakout lobes (1-3 m day^{-1}; Farquharson et al., 2015). Fourteen months after the onset of eruption (August 2012), the lava field covered an area of ~ 7 km^2 reaching a total volume of ~ 0.6 km^3 (Jay et al., 2014; Bertin et al., 2015). Mild explosive activity, characterized by mixed gas and ash jetting punctuated by Vulcanian blasts, accompanied the entire effusive phase (Shipper et al., 2013). Lava transport and lateral spreading was observed for several months after the termination of the eruption due to an efficient thermal insulation of the inner core (Tuffen et al., 2013; Farquharson et al., 2015). A rapid post-eruptive re-inflation was reported by Delgado et al. (2016) for the period 2012-2015 based on ground deformation inferred from InSAR.

3. Methods

3.1 MIROVA system

MIROVA (Middle Infrared Observation of Volcanic Activity; www.mirovaweb.it) is an automated global hot spot detection system (Coppola et al. 2016) based on near-real time ingestion of Moderate Resolution Imaging Spectroradiometer (MODIS) infrared data. Two MODIS instruments carried on NASA's Terra (EOS-AM) and Aqua (EOS-PM) satellites provide daily global observation at 16 infrared spectral channels. These instruments deliver approximately 4 images per day, with a nominal spatial resolution of ~ 1 km at nadir. The MIROVA system completes automatic detection, location and quantification of high-temperature (> 200°C) thermal anomalies related to volcanic activity, within 1 to 4 hours of each satellite overpass (Fig. 2a). MIROVA implements a hybrid algorithm using spectral and spatial principles to identify pixels contaminated by thermally anomalous features (see Coppola et al., 2016 for details). When pixel(s) are detected, MIROVA automatically calculates the total "above background" Middle Infrared Radiance (ΔL_{MIR}):

$$\Delta L_{MIR} = \sum_{i=1}^{i=n} L_{MIR,i} - L_{bk,i} \qquad \text{[equation 1]}$$

where L_{MIR} is the MIR radiance of the active pixel *i* (MODIS bands 21 or 22 centered at 3.959 μm), L_{bk} is the background MIR radiance (obtained from not contaminated, adjacent pixels) and *n* is the number of detected pixels. The "above background" MIR radiance thus provides a bulk measurement of the spectral radiance (W m^{-2} sr^{-1} μm^{-1}) emitted by the hot surface(s) in the 4 μm region of the electromagnetic spectrum (Fig. 2b). This last is then converted into Volcanic Radiative Power (VRP, in Watt) by using the "MIR method" (Wooster et al., 2003):

$$VRP = 18.9 \times A_{PIX} \times \Delta L_{MIR} \qquad \text{[equation 2]}$$

where A_{PIX} is the pixel's area (1 km^2 for MODIS), and 18.9 representing the constant proportionality (m^{-2} sr μm), derived from the linear relationship (± 30%) between spectral radiance and radiant power, for hot target having integrated temperature between 600 and 1500 K (Wooster et al., 2003).

During the Cordón Caulle eruption (1 June 2011 - 31 August 2012), the MIROVA system detected 619 alerts over a total of 2983 MODIS overpasses (~ 21%), with VRP spanning from less than 1 MW to more than 5000 MW (Fig. 2c). However, the visual inspection of all the alerted images facilitated identification of a large number of data acquired in cloudy conditions (143 images), and/or under poor geometrical conditions (i.e. high satellite zenith; 208 images) that strongly deformed and affected the thermal anomaly at ground level. We thus selected 268 high quality images (~ 43% of alerted images; ~ 9% of the total MODIS overpasses; 1 alert every 2 days, on average) that were used to calculate the total volcanic radiant energy (VRE) produced by the eruption (Fig. 3). As demonstrated by Massimetti et al. (2017), the trapezoidal integration of VRP signal related exclusively to supervised images (rather than to the whole unsupervised dataset), provides a robust and more accurate quantification of the total energy radiated by the eruptive events.

Figure 2

3.2 Landsat 7 ETM+ Thermal Analysis

A sequence of thermal images, acquired by the Enhanced Tematic Mapper plus (Landsat 7 ETM+) is also presented in Fig. 3b-i. This sensor provides multispectral images in 7 spectral channels (from visible to infrared) with a spatial resolution of 30 m (plus a pancromatic channel with 10 m resolution). Here we used the channel 6, centered at 11.5 μm, that offered a synoptic view of the thermal state of the CC lava flow during the eruption. By tracing the distinct boundary between the background and the saturation level (about 78 °C; Donegan and Flynn, 2004) the thermally active zones of the flow field were visualized (Fig. 3b-i). Despite a systematic flaw in all the ETM+ images acquired after May 2003 (diagonal data gaps prevent a complete view of the flow field), the images shown in Fig. 3b-i facilitates improved tracking of the sources of the VRP identified by MODIS.

Figure 3

4. Results

4.1 Thermal output of the 2011-2012 Cordón Caulle eruption

During the initial intense explosive phase (4-15 June 2011; gray field in Fig. 2c), MODIS-MIROVA discontinuous alerts (27 alerts in total), with the radiant power reaching very high values (VRP > 1000 MW) several time. In this first week of strong explosive activity, the detections were mostly plume-contaminated, thus providing only a minimum estimate of the radiant power generated by the active vent(s), where incandescent material was continuously ejected during explosive activity (Silva-Parejas et al., 2012)..

In contrast, since 15 June 2011, the thermal output associated with the emplacement of the obsidian lava flow was systematically tracked by MIROVA alerts (Fig. 3a). The radiant power reached the maximum of 915 MW on 21 June, 6 days after the beginning of the lava effusion. Hence, the thermal radiance started to decline gradually until September 2011 when the VRP was reduced to ~100 MW. The slow declining trend was interrupted in early October 2011 when the VRP gradually increase for about 4 weeks reaching again 200 MW in mid November. On 26 November 2011, an isolated peak of 634 MW marked a new breakout (Fig. 3a). This peak was followed by a declining pattern similar to the one observed during the beginning of the eruption phase. Small fluctuations were still recorded by February 2012 (between 100-150 MW) but between April and July 2012 the VRP declined definitively to less than 5 MW, likely in correspondence of the end of the effusion. This reduction in output corresponds to the lowering of the alert code from orange to yellow (Fig. 2c).

By integrating (trapezoidal integration) the dataset of suitable images, collected during the effusive phase between 15 June 2011 and 31 August 2012 (408 days, excluding the explosive and plume injection phase), we calculated that the Cordón Caulle lava flow radiated approximately 2.75×10^{15} J into the atmosphere, with a mean radiant flux of about 73 MW (Fig. 3a).

Figure 3

4.2 Radiant density of CC obsidian lava flow

Satellite-based thermal data have been widely used to estimate heat flux and lava discharge rates during effusive eruptions (see Harris, 2013 and references therein). The basic principle of this method relies on a mutual relationship between effusion rates, active flow area and the thermal flux that has been well documented (Pieri and Baloga, 1986; Wright et al., 2001; Harris and Baloga 2009, for details). In particular, after a certain transient time required to reach thermal equilibrium inside an active lava flow (Garel et al., 2012, 2016), the thermal energy radiated (VRE) can be related to the erupted lava volume (Vol) throughout a best-fit parameter (Coppola et al., 2013).

$$c_{rad} = \frac{VRE}{Vol} \qquad \text{[equation 3]}$$

where c_{rad} (hereby called radiant density) is an empirical that embeds the appropriate rheological, insulation and topographic conditions for the studied lava flow. Hence, by knowing the energy radiated during an eruption and the volume of the erupted lava, it is possible to infer the appropriate radiant density that characterizes a lava flow.

Systematic measurements of CC lava flow growth (Bertin et al., 2015) throughout the effusive phase, were combined with MIROVA radiance data. These datasets facilitate the calculation of radiant energy (VRE) for each independent volume measurement (Fig. 4a) and assess the evolution of the radiant density (equation 3) during the eruption (Fig. 4b).

As a whole, we observe a very high correlation ($R^2 = 0.98$) between VRE and volume, with a best-fit (linear interpolation) c_{rad} equal to ~ 4.9×10^6 J m^{-3} (Fig. 4c). Notably, the radiant density increased steadily during the first two weeks of extrusion (inset of Fig. 4b), and then stabilized to the best-fit value reported above (± 18%) until the end of the eruption (Fig. 4b).

The ratio between radiant and volumetric flux of active lava bodies is mainly controlled by their bulk rheological properties (Coppola et al., 2013), with low-viscosity basaltic lava flows exhibiting the highest value of c_{rad} (1-4 $\times 10^8$ J m^{-3}) and viscous silicic flows represented by the lowest end-member (< 1×10^7 J m^{-3}). Coppola et al. (2013) provided an empirical method to calculate the radiant density of a lava body (± 50%), on the basis of the silica content of erupted lavas, the latter being considered a first-order proxy of its bulk rheological properties:

$$c_{rad} = 6.45 \times 10^{25} \times \left(X_{SiO_2}\right)^{-10.4} \qquad \text{[equation 4]}$$

where X_{SiO2} is the silica content of the erupted lavas (wt %). For Cordón Caulle lavas (X_{SiO2} = 70 wt%; Castro et al., 2013), we calculated a radiant density of 4.2 (±2.1) $\times 10^6$ J m^{-3}, in strong agreement with those obtained from eq. 3 (Fig. 4d).

Figure 4

4.3 Effusive trend of CC 2011-2012 eruption

By using a radiant density equal to 4.9×10^6 J m^{-3}, we calculated the effusion rates trends for the CC 2011-2012 eruption, according to:

$$TADR = \frac{VRP}{c_{rad}} \quad \text{[equation 5]}$$

where TADR is the time averaged lava discharge rate (Coppola et al., 2013).

The evolution of TADR is compared in Fig. 5 with the topographic estimates provided by Bertin et al. (2015) and indicates the robustness of the thermal approach in tracking the variations of the extrusive process, during an ongoing silicic eruption.

The MODIS-derived effusion rates show a general waxing-waning trend, typically observed during pressurized eruptions (Wadge, 1981). The exponential decay of effusion rates is particularly evident during the first 4 months of activity when the TADRs declined from ~ 100 m^3 s^{-1} (on late June 2011) to ~ 15 m^3 s^{-1} (on late September 2001). However, between October and November 2011 our data suggest the occurrence of a slight increase in the effusive activity, that reached TADR values of 40 - 50 m^3 s^{-1} (Fig. 5a). The inspection of ETM+ images suggests that this phase was accompanied by the recrudescence of the surface activity in proximity of the vent, and emplacement of new lava lobe(s) at the northwestern flow margins (Fig. 3d-e). In subsequent months, the extrusion of lava slowed and was characterized by the emplacement at the northeastern lava flow unit and temporary breakouts at the margins of the compound flow field (Fig. 3g-i).

Similarities are noted between MODIS data and the amplitude of the quasi-harmonic tremor (Bertin et al., 2015) associated to the effusion of lava (initial waning stage followed by November 2011 pulse; Fig. 5a). The altitude of the erupted plumes, tracked by the Buenos Aires Volcanic Ash Advisory Center (VAAC; GVP, 2013), also correlate to MODIS output. The remarkable correspondence between lava discharge rate, seismicity and plume height (Fig. 5), point towards a common origin of the observed trends until November 2011. However, this relationship requires exogenous growth of the flow field (i.e. lateral expansion of the flow margin rather than inflation). Accordingly, we suggest the MODIS-derived lava discharge rate pulse recorded on late November 2011, represents the buffered response of the compound flow field to a real increase in magma flux at the vent, occurring 2-3 weeks earlier (25 October – 1 November). This would correspond to increases in the harmonic tremor and plume injection altitude indicative of enhanced activity (Fig. 5b-c).

Figure 5

5. Discussion

The results presented here outline that during the CC eruption, the MIR-derived radiant power (VRP) was strongly correlated to the effusive process (Fig. 5). In particular, we found that the timescale over which the thermal proxy becomes stable (i.e. the c_{rad} reaches a quasi-steady value) was approximately two weeks (Fig 4c). This transient time likely reflects a buffered thermal response of the bulk, viscous lava flow to shorter variations of lava emission at the vent, as inferred for example by variations of tremor amplitude (Fig. 5b) or plume elevation (Fig. 5c).

The timescale calculated here is much shorter than the one modelled by Garel et al. (2012), according which thermal equilibrium during emplacement of lava domes or silicic domes is reached only after several years. Garel et al. (2016) effectively suggest that the heat radiated by the whole lava surface of viscous lava bodies may not reach a steady state emission (very long transient time), and should not be used to calculate TADR. However, the same author also suggest that if only the hottest and younger portions of the flow field is considered, the ratio between radiant flux and discharge rate (i.e. c_{rad}) reaches a steady-state more rapidly, and the transient time becomes shorter. This important conclusion implies that the wavelength (and method) used to calculate the radiant flux is fundamental in determining what portion of the lava field is considered active, and what is the appropriate transient time.

As argued by Coppola et al. (2016), the use of the MIR method (Woster et al., 2003) to calculate the radiant power of active lava flows (characterized by a continuum of surface temperatures, from the effusion temperature to the background), relies on the notion that the flow surfaces at temperatures below 500-600 K do not contribute substantially to the pixel-integrated MIR radiance. Accordingly, the VRP estimated using equation 2 does not provide the radiant power of the whole lava surface, but more likely of smaller, younger and hotter portions of the flow field (cf. Coppola et al., 2010). As shown by the Landsat images (Fig. 3c), in the case of long-lived viscous lava bodies, these areas are restricted to the vent area, where the magma is extruded, as well as to active lobes at the flow margins, shear fracture zones and hot cracks within the upper surface (Bernstein et al., 2013).

The timescale of ~ 15 days represents the temporal window over which the discharge rate should be averaged (TADR), when applying the MIR-derived thermal proxy to viscous lava bodies similar to the CC lava flow. Accordingly, a single TADR measurement does not necessarily indicates sharp variations in the effusion rate at the vent, but may only reflect local surge(s) of lava, such as from temporary breakouts at the margins of the compound flow field. Such a mechanism of emplacement was recurrently observed during the CC eruption, with a significant evolution of breakout lava observed over a period of only 6 days (Tuffen et al., 2013). This is possibly a common feature of the obsidian flows that may affect the short-term thermal emission of the flow surface, thus causing a higher variability of a single measurement (gray circles in Fig. 5a). On the other hand, variations in viewing geometry of sun-synchronous satellites, such as MODIS, have been recognized by Flower et al. (2016) as a possible source of high frequency (< 8 days) non-geophysical radiance cycles. Despite selected only images with good viewing geometry, this non-volcanic cyclic behavior may still partially affect our analysis. Therefore, when the TADR values are averaged over an appropriate timescale, the local and temporary flow dynamics, as well as the noise created by sensor viewing geometry, become smoothed, and the MODIS-derived trend better reflects the effusive process at broad-scale (blue line in Fig. 5a). This suggests that a radiant density of ~ 5 × 10^6 J m^{-3}, probably characterizes also the spreading and cooling processes of other obsidian lava flows, whose bulk viscosities (~10^{10} Pa s) and emplacement styles are similar to the ones observed at CC (Farquharson et al., 2015).

One of the most interesting feature of the CC eruption was the hybrid and coeval explosive-effusive activity that led to emplacement of the large obsidian lava flow during sustained vulcanian ash emissions (Castro et al., 2013; Shipper et al., 2013). As stressed by Shipper et al., (2013), this coupled activity contrasts with most of the models that assume the explosive-effusive transition, as composed by two end-member styles, separated in time and resulting from contrasting mechanisms. The correlation observed between the tremor amplitude, plume height and the buffered MODIS-derived effusion rates (Fig. 5), provides new elements to interpret this hybrid activity and suggests that the explosive and effusive processes were fed by a common pressure source.

The overall effusive trend of the CC eruption (exponential decay) is indicative of a pressurized eruption (Wadge, 1981) and is consistent with the sin-eruptive deformation data suggesting magma withdrawal from one or multiple sources located between ~ 4 km and ~ 6 km depth (Jay et al., 2014).

Here we modeled the MODIS-derived cumulative volume according to an asymptotic exponential growth curve that is typical for such type of eruptions (Wadge, 1981):

$$V(t) = V_e\left(1 - \exp\left(\frac{t}{\tau}\right)\right) \qquad \text{[equation 6]}$$

where V_e is the excess magma volume inside the pressurized chamber, and τ is the decay time constant. Our best-fit regression (R^2 = 0.984) indicates an initial excess volume V_e, equal to ~ 0.75 km^3, and a time constant of ~205 days (Fig. 6a). Since the final volume of erupted lava was only ~ 0.6 km^3, the above model suggests that ~ 0.15 km^3 of magma remained unerupted after the end of the eruption. This value is very similar to the volume of magma (~ 0.125 km^3) that was intruded inside the edifice after the eruption (between March 2012 and April 2015), as documented by the post-eruptive deformation data (Delgado et al., 2016). According to this model, a blockage in the conduit, or in the magma path, would provide a possible link between the termination of the eruptive phase and the subsequent rapid reinflation of the volcano. Analysis of residuals (Fig. 6a) suggests that two montly-long cycles were overprinted on the whole exponential trend. Although we may not exclude that these cycles could be linked to exogenous growing process of the lava field, cyclic behaviors are frequently observed at silicic volcanoes and could be related to non-linear processes (degassing, crystallization, rheological stiffening) acting within the plumbing system (Denlinger and Hoblitt, 1999).

On the other hand, and on the basis of the correlation with tremor amplitude and plume height (Fig. 5), the effusive trend of CC eruption could be considered as composed by two distinct stages (*Stage 1*: 15 June- 31 October 2014; *Stage 2*: 1 November 2014 –31 August 2012, respectively; Fig. 6**).** In this case, our best-fit regression analysis indicates two very similar stages, characterized by Ve of ~0.360 and ~0.265 km^3 and time constants τ equal to ~ 62 and ~ 73 days, respectively (Fig. 6b). This two-stages model would be consistent with tapping of distinct but interconnected melt bodies, which is in agreement with a large and complex plumbing system, eventually composed by distinct but hydraulically connected compartments (e.g., Gudmundsson, 2012), as suggested by deformation pattern (Jay et al., 2014; Delgado et al., 2016) and geochemical analysis of erupted magmas (Alloway et al., 2015).

6. Conclusions

The excellent correlation (R^2 = 0.98) between cumulative volumes and radiant energy, provides a significant validation of the thermal proxy for the Cordón Caulle obsidian flow. We found that the equilibrium between volumetric and radiant fluxes was reached after the first 15-20 days of activity, and remained relatively stable (c_{rad} =4.9 ± 0.9 × 10^6 J m^{-3}) throughout the rest of the eruption. We suggest that during long-lived silicic eruptions, the satellite-derived effusion rates must be time-averaged over periods of at least 15 days. This correction allows filtering the cyclic noise related to satellite viewing conditions (Flower et al., 2016), and permits to smooth local surge(s) of lava from temporary breakouts unrelated to the magma flux at the vent. The absolute value of the coefficient of proportionality (i.e. c_{rad}, radiant density) is significantly lower than those found for basaltic lava flows (1-4 × 10^8 J m^{-3}) and falls well in the range of typical c_{rad} of viscous silicic flows (2-10 × 10^6 J m^{-3} ; Coppola et al., 2013). This suggests that the spreading and cooling processes of lava bodies can be essentially expressed through a viscosity-dependent relationship, linking the radiant energy and the erupted lava volume. For any type of lava flow, if the timescale and the appropriate range of c_{rad} values can be reasonably inferred (from direct measurements (eq. 3) or empirically (eq.4)), the effusion rates and the erupted lava volumes can be calculated in near real time from satellite thermal data. This methodology provides a new tool for tracking effusion rate trends not only for basaltic eruptions (e.g. Coppola et al., 2017) but also for silicic, flow-forming eruptions whose effusive dynamic is much less studied. In the case of CC eruption, the MODIS-derived effusion rates correlate with the seismic tremor and the plume height, thus suggesting a common pressure source for the coeval effusive and explosive activities. Modelling of the effusion rate trend allow us to suggest alternatively an exponential discharge dynamic, typical of pressurized eruptions (Wadge, 1981), characterized by incomplete magma withdrawal and linked to the post-eruptive inflation phase; or a more complex magma discharge, probably tapping different interconnected magma bodies.

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Figure Captions

Figure 1 – (a) Location of Cordón Caulle Volcanic Complex (CCVC) on the Southern Andes Volcanic Zone, with the Cordón Caulle (CC) fissures system lying between the Cordillera Nevada, on the NW, and the Puyehue stratovolcano on the SE. The lava flow related to the 2011-2012 eruption is shown in red (shaded relief map from Google Maps). (b) A detailed view of the 7.2 km^2 obsidian lava flow emplaced throughout the eruption (image from Google Maps).

Figure 2 – (a) Example of MODIS images (in transparency on Google Earth) acquired over CCVC on 30 December 2011 (05:55 UTC) and elaborated by the MIROVA system (Coppola et al., 2016). The image displays the MIR radiance recorded at 3.959 μm (MODIS band 22), over an area of 50x50 km centered on Puyehue volcano (pixel resolution is 1 km). Thermal anomalies appear as bright pixels at the eruptive site, while the ash volcanic plume, directed toward north, is represented by black (cold) pixels. (b) Zoomed view over the CC lava flow (dashed black line) showing the distributions of alerted pixels detected by the MIROVA algorithm (black contour line). The total "above background" MIR radiance, ΔL_{MIR}, is equal to 7.78 W m^{-2} sr^{-1} μm^{-1}, corresponding to a VRP of 147 MW (eq. 2). (c) Volcanic Radiative Power (VRP) recorded during the 2011-2012 CC eruption (on log scale). The horizontal color bar refers to the alert codes provided during the

eruptive crisis by the *Servicio Nacional de Geología y Minería*. The gray field outlines the initial phase (4 – 15 June 2011) characterized by intense explosive activity and ash emission.

Figure 3 – (a) Radiant power (left axis) and energy (right axis) recorded by MODIS during the effusive phase of the 2011-2012 Cordón Caulle eruption (15 June 2011 – 31 August 2012). Gray circles represent VRP of single selected images. The blue line (7 points moving average) describes the long-term pattern of the radiant flux between June 2011 and August 2012. (b) Sequence of thermal images derived from Enhanced Tematic Mapper Plus (Landsat 7 ETM+) acquired on 2011-2012 over CC lava flow. Colors represent the "above background" radiance, recorded at 11.5 μm (ETM+ Channel 6). White pixels represent flow surfaces at temperature higher than the saturation level (pixel integrated temperature of ~78 °C). Black contours outline the final extension of the lava flow. Diagonal data gaps are due to failure of Landsat 7 Scan Line Corrector (SLC) occurred in May 2003.

Figure 4 – (a) Temporal evolution of CC lava flow volume (black squares) and radiant energy measured by MODIS (red circles). Volume data from Bertin et al. 2015; (b) Temporal evolution of the radiant density (eq. 3) throughout the eruption. After the first 15 days of activity the radiant density reaches an almost steady value ($\sim 4.9 \times 10^6$ J m^{-3}), representing by best-fit relationship (c) between Volcanic Radiant Energy (VRE) and erupted volume (Vol); (d) Relationship between radiant density and silica content of 28 lava bodies (gray squares) analyzed by Coppola et al. 2013. The high silica Cordón Caulle obsidian flow (yellow star) is characterized by a radiant density in excellent agreement with those predicted by the eq. 4 (black dashed line).

Figure 5 - (a) Time-Averaged Discharge Rate (TADR) estimated for the effusive stage of 2011-2012 Cordón Caulle eruption by using a radiant density $c_{rad} = 4.5 \times 10^6$ J m^{-3} (eq. 3). Single MODIS-derived measurements (gray circles) likely tracked the continuous occurrence of short-lived, local

breakouts that produced the sharp fluctuations of the TADR. The weekly average (blue line) better reproduces the extrusive process as measured by the volumes estimates of Bertin et al., 2015 (black squares). (b) Quasi-harmonic tremor (maximum reduced displacement; RD) recorded between June and December 2011 (modified from Bertin et al., 2015); (c) Plume height recorded during the 2011-2012 CC eruption (data from the Buenos Aires Volcanic Ash Advisory Center VAAC and SERNAGEOMIN; source Global Volcanism Program, 2013).

Figure 6 – MODIS-derived cumulative volume (blue circles) measured during the CC eruption. (a) A single stage magma discharge model (red line, equation 6) indicates an excess magma volume V_e = 0.75 km^3 and decay constant τ = 205 days. At the end of the eruption (31 august 2012) only 0.6 km^3 were erupted, thus implying a volume of unerupted magma equal to 0.15 km^3. The occurrence of two sub-cycles (as evidenced by residuals) may result from non-linear processes inside the plumbing system. (b) Two-stages magma discharge model (red lines). Stage 1 (15 June- 31 October 2014) is characterized by V_{e1} = 0,360 km^3 and τ_1=62 days; Stage 2 (1 November 2014 –31 August 2012), is characterized by V_{e2}= 0,266 km^3 and τ_2=73 days. The consecutive eruptions of two interconnected magmatic sources (compartments), could be at the origin of this trend.