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Measuring effusion rates of obsidian lava flows by means of satellite thermal data

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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.

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 may reveal 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 parameters 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; Zakšek 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 and Griffiths, 1998; Griffith, 2000;

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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 spanning from hours to days is 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 times 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 characterized by the superimposition of the Quaternary tectonic regime (see Cambrano 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 characterized 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).

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 characterized 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

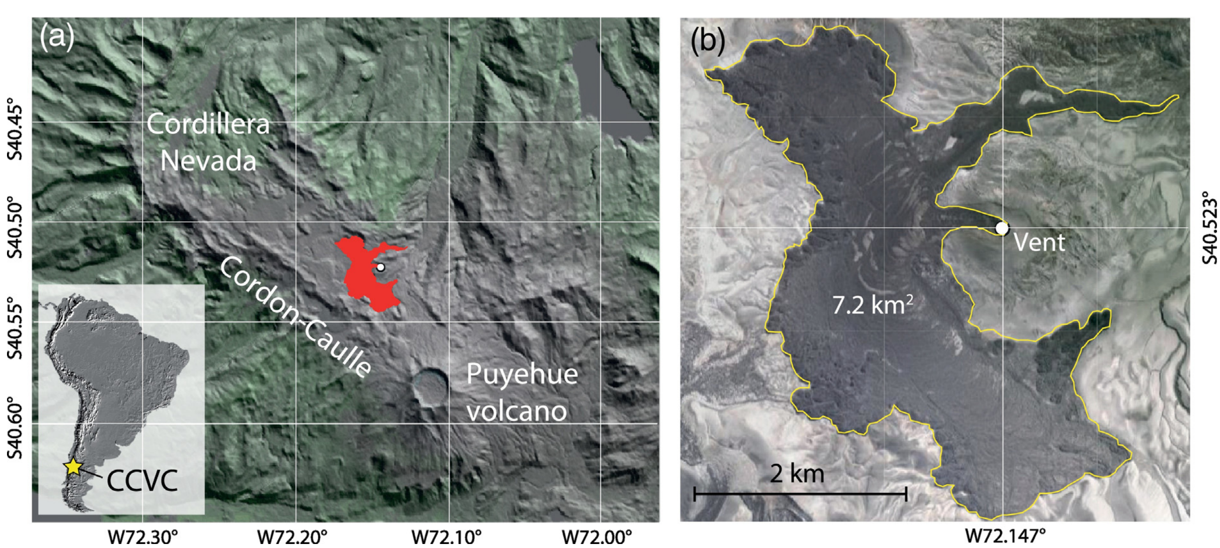

Fig. 1. (a) Location of Cordón Caulle Volcanic Complex (CCVC) on the Southern Andes Volcanic Zone, with the Cordón Caulle (CC) fissures system lying between the Cordillera Nevada, on the NW, and the Puyehue stratovolcano on the SE. The lava flow related to the 2011–2012 eruption is shown in red (shaded 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). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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