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Monitoring the time-averaged discharge rates, volumes and emplacement style of large lava flows by using MIROVA system: the case of the 2014-2015 eruption at Holuhraun (Iceland)

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25 Abstract

The 2014-2015 eruption at Holuhraun has produced more than 1.5 km³ of basaltic magma and can be 26 considered one of the major effusive events of the last two centuries in the world. During this eruption 27 the MIROVA system (a volcanic hot-spot detection system based on MODIS middle infrared - MIR 28 - data) has been used to detect and locate the active portions of the lava flow(s), and to measure the 29 heat radiated by the growing lava field. According to these data the eruption was characterized by a 30 slow decay of the radiant power, accompanied by a change in the lava transport mechanism that 31 shifted from open channels, at the beginning of the eruption, to lava tubes, during the last months of 32 activity. Despite the evident evolution of lava transport mechanism, we found that the overall 33 decreasing trend of the thermal flux was mainly controlled by the exponential decline of lava 34 discharge rates, while the increasing insulation of the flow field had a strong impact in transporting 35 efficiently the lava at the distal flow front(s). Our results suggest the apparent time averaged lava 36 37 discharge rates (TADR), derived from satellite thermal data, may fluctuate around the real effusion rate at the vent, especially in the case of large lava flows emplacing in nearly flat conditions. The 38 39 magnitude and frequency of these fluctuations are mainly controlled by the emplacement dynamic, 40 (i.e. occurrence of distinct major flow units), while the transition from channel- to tube-fed lava transport mechanism play only a minor role ($\pm 30\%$) in the retrieval of *TADR* using MIR data . When 41 the TADR values are integrated to calculate erupted lava volumes, the effects of pulsating 42 emplacement dynamic become smoothed and the eruptive trend become more clear. 43

We suggest that during the Holuhraun's eruption, as well as during many other effusive eruptions, the MIR-derived radiant flux essentially mimic the overall trend of lava discharge rates, with only a minor influence due to the emplacement style and evolving eruptive conditions. From a monitoring and operational perspective, MIROVA demonstrates to be a very valuable tool to follow and, possibly, forecast the evolution of on-going effusive eruptions.

On August 29th 2014, one of the largest effusive eruption of the last 3 centuries took place along the 51 Eastern Volcanic Zone (EVZ) of Iceland, about 45 km north-east of Bárðarbunga volcanic system 52 (Gudmunsson, et al., 2014). The new eruption followed 15 days of sustained seismicity and 53 accompanied the propagation of a 45 km long dike (Sigmundsson et al., 2015) that unlocked an 54 historical eruptive path named Holuhraun (Sigurðsson and Sparks, 1978). The emission of lava 55 persisted at very high rate for 180 days up to February 27th, 2015 when the activity was declared over 56 (Gislason et al., 2015). The eruption was characterized by a slow decay of effusion rate (Coppola et 57 al., 2017) that accompanied a coeval slow subsidence of the Bárðarbunga caldera (Gudmundsson et 58 al., 2016). The clear link between the two processes provided evidences of an inelastic eruption 59 whereby the lateral magma withdrawal was essentially linked to the gravity-driven collapse of the 60 summit caldera (Coppola et al., 2017, Gudmundsson et al. 2016). About 84 km² of nearly flat land 61 was covered by the new lava field that reached a maximum extend of about 18 x 5 km (Figure 1) and 62 63 thickness up to 40 m (Gislason et al., 2015, Pedersen et al. 2017).

The prohibitive environmental conditions that might characterize these latitudes made field 64 observations at the eruptive site very hard, especially on a continuous basis and for several months 65 during the winter time. In these conditions, space-based thermal data have been extremely useful 66 since they allowed a safe detection, location and quantification of the radiant flux produced by the 67 effusive activity. In particular, infrared data acquired by MODIS (Moderate Resolution Imaging 68 Spectroradiometer) and elaborated through the MIROVA volcanic hotspot detection system, 69 70 (Coppola et al., 2016; <u>www.mirovaweb.it</u>), were delivered to the Icelandic Meteorological Office (IMO) as part of its daily operational monitoring activity of the Holuhraun eruption. 71

Since the beginning of the eruption the main tasks of satellite thermal data were: (i) to provide information about the location of active lava flow areas and front, (ii) to give an estimation of lava discharge rates and erupted volumes and finally (iii) to identify the ongoing effusive trend (steady,

waning or waxing). The latest two points became a priority after a couple of months when the winter 75 season and the low-light conditions made the eruptive site hardly accessible and field observations 76 became more and more rare and difficult. The calculation of effusion rates from satellite thermal data 77 (the so called "thermal proxy"), become one of the main topic discussion among a thermal remote 78 sensing group, established in that occasion by Dr. Thor Thordarson (Harris et al., 2016a). One of the 79 main questions discussed within the group was "whether the subtle, but persistent decay of thermal 80 flux indicated by satellite measurements, was caused by a real, slow decline of the effusion rate or 81 reflected the increasing insulation of the growing lava field and the development of a lava tube system 82 (Pedersen et al., 2017) 83



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Figure 1. (a) Location of the Bárðarbunga-Holuhraun volcanic system showing the ice covered, 10-km-wide caldera of Bárðarbunga and the 2014-2015 lava filed at Holuhraun. (b) Example of MODIS-derived thermal image (spatial resolution of 1 km) showing the Brightness Temperature at 4 μ m (BT4) recorded on February 03rd, 2015 over the Holuhraun lava field (white line). The star indicates the approximate location of the vent. (c) Temperature profile along W-E direction, obtained by calculating the maximum BT4 along each vertical (N-S) line. The position of the flow front is marked by the easternmost thermally anomalous pixel (see the text for details).

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In this paper we present time-averaged lava discharge rates and volumes, derived by using MIROVA system, and we compare the results with field and independent measurements collected during and after the Holuhraun eruption. The comparison reveals the role of changing emplacement style in the lava discharge rates calculation and outlines the contribution of MIROVA in safely tracking this large effusive eruptions from space.

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2. Time-averaged discharge rates from satellite thermal data: background and open questions

The relationship between effusion rates and thermal emissions of lava flows has received increasingly 103 attention during the past three decades (a full list of 46 papers published between 1990 and 2005 is 104 reported in Harris 2013). The methods, limits and applications of this approach are part of a book 105 expressly focussed on detecting, modelling and responding to effusive eruptions (Harris et al., 2016b), 106 whereas exhaustive overview of the physic behind mass and energy flow through a lava flow system 107 is provided by a series topical works (Pieri and Baloga 1986, Crisp and Baloga 1990, Harris et al., 108 1997, Wright et al., 2001, Harris et al., 2007, Harris and Baloga 2009; Dragoni and Tallarico 2009, 109 Coppola et al, 2013; Garel et al., 2012, 2014, 2015, Tarquini (2017), among others). Here, we outline 110 the basic principles of this technique and we summarize the open questions that have been addressed 111 112 in this work.

To describe volumetric flow rates of erupted lavas, we use the terminology given by Harris et al. (2007). We use the generic term *effusion rate*, to describe the instantaneous rate at which lava is erupted from the vent at any time. The term *mean output rate* (*MOR*) is used to describe the final volume of erupted lava divided by the total duration of the eruption. Finally, we used the term *timeaveraged lava discharge rate* (*TADR*) to describe the volume of lava emplaced during a specific time interval (Harris et al., 2007). This definition better applies to the use of satellite-based methods, for measuring the changes in lava volume over a given period of time prior the image acquisition (Wrightet al., 2001).

Currently, two main methods exist to estimate *TADRs* from space-based thermal data; the method of Harris et al. (1997), simplified later by Wright et al. (2001), and the method of Coppola et al., (2013). Both the methods rely on the original heat balance approach (Pieri and Baloga, 1986), stating that the *mean output rate MOR* ($m^3 s^{-1}$) of a cooling-limited lava flow, is related to its final plan area *A* (attained when the flow achieves its final length, *L*), by:

126

127
$$MOR = \frac{\varepsilon \sigma T_e^4}{\rho C_p (T_0 - T_{stop})} A(L)$$
(eq. 1)

128

129 where ρ (kg m⁻³) and C_p (J kg⁻¹ K⁻¹) are the bulk density and heat specific capacity of lava, 130 respectively, T_e (K) is the effective radiation temperature of the flow, T_0 (K) is the lava eruption 131 temperature, and T_{stop} (K) is the temperature of the flow front at the time the flow has cooled to a halt. 132 In this framework, the effective radiation temperature is defined as "the temperature at which the flow 133 would radiate if it had a constant surface temperature throughout the emplacement of the flow" (Crisp 134 and Baloga, 1990).

Harris et al., (1997), applied this approach to satellite thermal data, developing what is actually called 135 the "thermal proxy". Further works (Wright et al., 2001; Harris et al. 2007, 2009) refined and 136 simplified this method suggesting that the equation 1, when applied to satellite radiance data, provides 137 discharge rates that are not necessarily averaged over the total duration of an eruption, but rather over 138 "some time" prior to the satellite acquisition. Here, the effective radiation temperature, Te, takes a 139 specific meaning, since it represents the average surface temperature over "some time" prior to the 140 141 satellite acquisition, weighted according to the radiative heat flux (Harris and Baloga, 2009). Accordingly, Harris et al., (2007) proposed to use the term "time-averaged discharge rate" (TADR), 142 in order to describe the discrete measurements of lava flux retrieved from single satellite thermal 143

images. Wright et al., (2001) also argued that all values except *MOR* (*or TADR*) and *A* are assumed
a priori in equation 1 so that the thermal proxy reduces to a simple relationship whereby:

147
$$TADR = Ax$$
 (eq. 2)

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Here *x* is an empirical parameter (m s⁻¹), that describes the appropriate compositional flow parameters (ρ , C_p) as well as thermal insulation (T_e) and cooling (T_0 - T_{stop}) conditions (cf. Harris and Baloga 2009). In this formulation the area of the active flow area, A (m²) is also dependent on the insulation condition expressed by T_e , and is directly retrieved from the pixel integrated spectral radiance, R_λ (W m⁻² sr⁻¹ µm⁻¹), according to:

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$$A = \sum_{i=1}^{npix} \frac{R_{\lambda} - L_{\lambda}(T_{bk})}{L_{\lambda}(T_e) - T_{\lambda}(T_{bk})} A_{pixel}$$
(eq. 3)

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where T_{bk} is the background temperature (K), L_{λ} is the Plank function for wavelength λ (W m⁻² sr⁻¹ µm⁻¹), and A_{pixel} is pixel area (1 km² for MODIS). By assuming two end-member radiating temperatures (T_e) for the hot and cold models (for example 500°C and 100°C for the channel- and tube-fed flow type, respectively), the equation 3 allows the user to calculate a range of plausible active flow areas, responsible for the observed radiance (Harris et al., 2007).

As stressed by Harris and Baloga (2009), the values for *x* have to be set on a case-by-case, thus leaving a wide arbitrariness to the user that may adjust all the unknowns in equation (1) to achieve a best-fit with available and independent field data. The TIR (thermal infrared) bands are generally used in this approach under the assumption that the surface area of high temperature cracks is small and provides a negligible contribution to the pixel integrated radiance at 10 μ m to 12 μ m (Harris and Baloga 2009). This approach (equations 2 and 3) was the one used by Bonny et al., (2018) to estimate the volume
of lava erupted during the 2014-2015 eruption at Holuhraun by using MODIS TIR data.

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The method of Coppola et al., 2013, does not hold with the calculation of active flow areas, but is based on the empirical relationship that directly links the *TADR* with the Volcanic Radiant Power (*VRP*) calculated via the MIR method (Wooster et al., 2003). The MIR-derived *VRP* is a measurement of the heat flux radiated almost exclusively by the portions of lava flows having effective temperature (T_e) above 600 K, and is calculated as:

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176
$$VRP = 18.9 \cdot A_{pixel} \cdot \sum_{i=1}^{npix} (R_{MIR,alert} - R_{MIR,bk})_i$$
 (eq. 4)

177

where $R_{MIR,alert}$ is the pixel integrated MIR radiance of the ith alerted pixel, $R_{MIR,bk}$ is the MIR radiance of the background, A_{pixel} is the pixel size (1 km² for the resampled MODIS pixels), and 18.9 is a constant of proportionality (see Wooster et al., 2003). The *TADR* is than calculated by using a single coefficient called radiant density (c_{rad} in in J m⁻³):

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183
$$TADR = \frac{VRP}{c_{rad}}$$
 (eq. 5)

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that describes the relationship between volumetric and radiant flux appropriate for the observed eruption (Coppola et al., 2013). By analyzing a large compositional spectrum of recent lava flows, Coppola et al., (2013) proposed an empirical method to calculate the c_{rad} , based on the silica content of the erupted lavas:

190
$$c_{rad} = 6.45 \times 10^{25} \times (X_{SiO_2})^{-10.4}$$
 (eq. 6)

191 where X_{SiO2} is the silica content of the erupted lavas (wt%).

This method allows to take into account the strong effects that the bulk rheology has on the spreading and cooling processes of active lavas, and, according to the authors, permit to estimates *TADR* with an uncertainty of \pm 50% (Coppola et al., 2013). Most importantly, it allows to calculate the appropriate radiant density, once the first chemical analysis of the erupted lavas become available (Coppola et al., 2017). Since the MIROVA system provides automatically the *VRP* (Coppola et al., 2016), the radiant density approach (equations 5 and 6) was the one used by Coppola et al., 2017 to estimate *TADR* and erupted lava volume during the Holuhraun eruption.

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Although the two methods derive from the original heat balance approach, valid for cooling-limited 200 lava flows (eq. 1), it is important to remark that they do not necessarily yield exactly the same results 201 (cf. Bonny et al., 2018, Coppola et al., 2017). This is because the wavelengths used by the two 202 203 methods are different (R_{TIR} and R_{MIR}, respectively) but also because of the arbitrariness of the input coefficients, as x for the Harris' method and c_{rad} for the Coppola's method. Nevertheless, both the 204 205 methods provide an upper and lower boundary estimates of TADR that are *linearly* related to the 206 pixel-integrated spectral radiances (cf. eq. 1 to 5). It follows that whatever the method used, a constant TADR would be translated into a constant radiance detected by space. 207

208 This point was challenged by recent laboratory experiments and physical modelling of cooling viscous gravity currents (Garel et al., 2012, 2014, 2015) according to which for a given magma 209 discharge rate the heat radiated by the flow surface reaches a steady value only after a transient time. 210 According to the cooling-limited flow model (eq. 1), this transient time would correspond to the time 211 required for the lava flow front to reach its maximum length (L) and to cool to a halt ($T_{front} = T_{stop}$). 212 Hence, during rapid changes of effusion rates the thermal signal would be "buffered" in time, because 213 it takes time for the higher flow rate to propagate downstream and cause perceptible increases in flow 214 area (Harris and Baloga 2009). The transient time thus reflect the dynamic response of the thermal 215 structure toward the appropriate cooling-limited conditions expressed by the new TADR vs. A 216

relationship (i.e. new steady-state condition). Tarquini (2017) also suggests that this transient time is
typical of non-equilibrium steady-state systems, and is related to a structural relaxation time that
operate particularly on long-lived lava flows. In this non-equilibrium framework, the active lava flow
units represent "dissipative structures" that promote significant fluctuations in the radiative power,
even in the case of a constant supply. Hence, the radiant flux would be modulated by a pulsating
emplacement dynamic, associated to the occurrence of flow diversions that resets the system further
from its maximum extension (cf. Tarquini 2017).

Other open questions remain challenging, especially for operational use of the thermal proxy during 224 effusive crisis. For example, based on its theoretical model, Garel et al. (2012) suggests that when 225 226 lava tubes form, the surface thermal signal will not reflect the flow dynamics, because the low crust temperatures do not reflect a potentially high flow rate of hot lava underneath. According to the 227 authors, this would pose a serious problem, since many lava flows exhibit evolving emplacement 228 229 styles throughout the eruption, often characterized by increasing insulation conditions and gradual formation of lava tubes. Similarly, it is still unclear how to determine whether an eruption has ceased 230 231 based on thermal data, or whether the lava stored underneath a cooled crust can potentially emerge 232 suddenly and spread rapidly (Garel et al., 2015). In these terms the 2014-2015 eruption at Holuhraun represents a key-case since allowed us to address all these points over the largest effusive eruptions 233 234 occurred in the past three centuries.

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236 **3. Methods: Analysis of MODIS-MIR data**

237 3.1 The MIROVA system

MIROVA (Middle Infrared Observation of Volcanic Activity) is an automated global hot spot detection system (<u>www.mirovaweb.it</u>) based on near-real time processing of Moderate Resolution Imaging Spectroradiometer (MODIS) infrared data (Coppola et al. 2016). The system completes automatic detection and location of thermal anomalies, and provides a quantification of the Volcanic

Radiative Power (VRP), within 1 to 4 hours of each satellite overpass. This is achieved through a 242 hybrid algorithm (fully described in Coppola et al., 2016) based on MIR radiance data ($\sim 4 \mu m$) 243 recorded at 1-km spatial resolution, as shown in Fig. 1b. Two MODIS instruments (carried on two 244 NASA's satellites: Terra and Aqua) deliver approximately 4 images per day for every target volcano 245 located at equatorial latitudes. However, due to the polar, sun-synchronous orbit, the two satellites 246 increase their sampling time at high latitudes, providing, at least 6 to 10 overpasses per day over 247 248 Iceland. An example of thermal images elaborated by the MIROVA system during the Holuhraun eruption is given in Fig. 1b. 249

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251 *3.2 Volcanic radiative power and energy of the 2014-2015 eruption at Holuhraun*

Between August 29th, 2014 and March 4th, 2015, MIROVA detected hotspots in 1105 images over a 252 total of 1623 MODIS overpasses above Iceland (~68.1%). The volcanic radiative power (VRP) ranged 253 from ~39.1 GW, during the initial stage of the effusion, to less than 10 MW just before the end of the 254 eruption (Figure 2a). During the course of the eruption, we visually inspected all the acquired scenes 255 and we identified a large number of images acquired in cloudy conditions, and/or under poor 256 geometrical conditions that strongly deformed and affected the thermal anomaly at ground level. 257 These images were discarded from further analysis (blue circles in Fig. 2a) so that a supervised dataset 258 of only 206 high-quality images (~12.7% of the total MODIS overpasses) was used to provide a 259 robust quantification of VRP produced by the eruption (red circles in Fig. 2a). As a whole we 260 estimated that the Holuhraun eruption radiated approximately 1.6×10^{17} J into the atmosphere (red 261 curve in Fig. 2b), with a time-averaged radiant flux of about 10.5 GW. 262



Figure 2. (a) Timeseries of *VRP* retrieved from MODIS-MIROVA system during the 2014-2015 eruption at Holuhraun. Blue circles represent data discarded because of cloudy conditions or poor viewing geometry. The data selected for *VPR* calculation are the white circles. The red line is a 5-points-moving average of *VRP*. A *VRP* below 10 MW coincides with the end of the eruption. (b) Volcanic Radiative Energy (*VRE*) calculated by trapezoidal integration of selected data only (red curve) or all the data (blue curve). Note the strong influence of data selection on the final total energy. Approximately 1.6×10^{17} J were radiated into the atmosphere (red curve), with a mean radiant flux of about 10.5 GW.

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272 3.3 Time-averaged discharge rates and volume calculation

During the course of the eruption, we calculated TADRs and erupted lava volumes by using the radiant 273 density approach described above (eq. 5 and 6). The preliminary chemical analysis of Holuhraun 274 lavas (SiO₂ = 50.5 wt%), provided in early September 2014 by the University of Iceland 275 (http://earthice.hi.is/bardarbunga 2014), were used to calculate (eq. 6) a radiant density comprised 276 between 0.62×10^8 and 1.86×10^8 J m⁻³. These two values allowed us to provide an upper and lower 277 boundary limits for lava volume calculation, with the mean value being the most likely (Fig. 3a). 278 Given a final VRE equal to 1.64×10^{17} J (Fig. 2b), this method provided a first, timely assessment of 279 the erupted lava volume equal to 1.75 ± 0.88 km³ (Fig. 3a). This was in good agreement with the flow 280 volume estimated a-posteriori ($1.4 - 1.6 \text{ km}^3$) by using independent datasets (Gislason et al. 2015, 281 Gudmundsson et al., 2016, Dirshel and Rossi, 2018; Bonny et al., 2018). The inferred satellite-282

derived *TADR* and erupted volumes were updated continuously and delivered via emails to the teams
of the IMO and University of Iceland in charge of the monitoring.

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287 Figure 3. (a) Lava volumes measured during the 2014-2015 eruption at Holuhraun. The colored field envelop the upper 288 and lower boundary limits calculated using the radiant density approach (eqs. 5 and 6). Best-estimate volume calculation 289 (blue circles), and relative uncertainty (±50%) were provided in near real time to IMO and University of Iceland. 290 Independent measurements of final lava flow volumes given by several authors are also shown. (b) Comparison between 291 lava field volume measured by MODIS (blue circles) and exponential models of erupted lava volume (Coppola et al., 292 2017) and caldera volume (Gudmunsson et al., 2016). The good correlation indicates a strong link between to the gravity-293 driven collapse of Bárðarbunga caldera and the gradual decrease of magma-static pressure driving the effusive eruption 294 at the vent (cf. Gudmunsson et al., 2016, Coppola et al., 2017, Dirsherl and Rossi, 2018).

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4. Eruptive trend derived from satellite thermal data

One of the most significant feature of this eruption was the overall exponential trend of the satellitederived cumulative volume (Fig. 3b). As outlined by recent studies, this trend mirrors almost perfectly the slow subsidence of the Bárðarbunga caldera floor (Fig. 3b) and suggests a strong connection between source caldera/reservoir dynamic, and the eruptive dynamics 45 km distant (Gudmundsson

et al., 2016; Coppola et al., 2017). According to these works, the exponential decay of effusion rates 302 was driven by a decrease of magma-static pressure, associated to the shrinking of the magma chamber 303 and the gravity-driven collapse of Bárðarbunga caldera. In this scenario, the instantaneous effusion 304 rate at the vent follows a perfectly exponential curve (blue line in Fig 4a) that has been used as a 305 benchmark for our MODIS-derived TADRs' (red line in Fig 4a). Hence, the residuals between the 306 two rates (observed - modeled; Fig. 4b) enhance temporary variations of the source process, or 307 instabilities of the thermal proxy due to lava flow emplacement dynamic. In the following section, 308 309 we discuss the effusive trend in the light of the evolving emplacement style observed in the Holuhraun lava field. 310

According to Pedersen et al. (2017) the Holuhraun eruption can be subdivided in three main phases,
characterized by evolving lava transport processes.

The phase 1 (31 August – 12 October 2014) was characterized by lava transport confined to open 313 314 channels that led the formation of four consecutive lava flows emplaced side by side (no. 1-4 in Fig 4b). During this phase the discharge rates measured on the field were comprised between 350 and 315 100 m³ s⁻¹ (Pedersen et al., 2017), in good agreement with satellite-derived values. The four flow 316 317 units reached distances of 16.9, 11.8, 16.3 and 11.0 km, respectively (Fig. 4a), and covered a total area of 58.31 km² (Pedersen et al., 2017). Given a flow field volume of 0.78 km³ estimated on October 318 12 (Fig. 3b), the mean flow thickness characterizing the Phase 1 was 13.4 m, consistent with the 319 thickness of each single flow units observed on the field (Pedersen et al., 2017). During this period 320 our TADRs measurements show the greatest oscillations around the modelled value (up to \pm 60%), 321 resulting in sharp variations exactly in correspondence of the activations of the distinct flow units 322 (Fig 4b). 323



Figure 4. (a) *TADR* derived from MIROVA data (white circles) by using the radiant density approach (eqs. 5 and 6). The blue line represents the best-fit exponential model (Coppola et al., 2017) hereby considered the real effusion rate at the vent. (b) Residuals flow rates (left axis) obtained by subtracting the model from the observations (i.e. MODIS-derived *TADR* minus modelled effusion rates). Note how the residuals oscillate around the model showing a decreasing amplitude through time. The timing and amplitude of the residual pulses are coherent with the occurrence and maximum length of

the main channel-fed flow units numbered from 1 to 8 (data from Pedersen et al., 2017). The three phase of the eruption
described by Pedersen et al., 2017 are also shown.

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The phase 2 (13 October – 30 November 2014) had lower effusion rates $(150 - 100 \text{ m}^3 \text{ s}^{-1})$ and was 334 characterized by the formation of a $< 1 \text{km}^2$ lava pond, that acted as a distributor of subsequent lava 335 flows (i.e. flows no. 5–8; Pedersen et al., 2017). These flow units reached gradually shorter distances 336 (11.7, 8.4, 7.1, 5.4 km, respectively) and were accompanied by satellite-derived TADRs showing 337 decreasing oscillation amplitudes (Fig. 4b). Towards the end of this phase the occurrence of *inflation* 338 339 *plateaus* provided the first evidences of a growing lava tube system, with satellite-derived TADRs becoming more stable (Fig. 5b). About 0.52 km³, of lava was erupted during this phase (Fig. 3a) 340 producing a net increment of the flow field area of 18.7 km² (Pedersen et al., 2017). By the end of 341 November the flow field reached an average thickness of 16.9 m. 342

During the third phase (1 December 2014 – 27 February 2015) the lava transport was mainly confined 343 to lava tubes which fed several breakouts and inflation plateaus along the initial flow units no. 1 and 344 2 (Pedersen et al., 2017). More than 19 km² of the flow field was resurfaced, with discharge rates 345 much more steady ($\pm 20\%$) and typically lower than 100 m³s⁻¹. A sharp reduction of TADR was 346 recorded since 27 January 2015 and preluded the end of the eruption occurred one month later, on the 347 27 February 2015 (Fig.4). This reduction was interpreted by Coppola et al., (2017) as due to the 348 gradual closure of the magma path once the overpressure inside the dike had dropped below a critical 349 value. The lava tube system distributed about 0.4 km³ during this phase, with the lava field reaching 350 a final extension of 85.4 km². The inflation and resurfacing processes that operated through the tube 351 352 system led the average flow thickness to increase up to 20.2 m.

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The emplacement of the major lava flows (phases 1 and 2) is outlined by the occurrence of apparent *TADR's* "pulses" (Fig. 4a) oscillating around the modelled value for effusion rate (Fig. 4b). Pulsating effusive activity has been recognized at several basaltic volcanoes and may results from different

processes such as pulsed magma supply, repeated accumulation and collapse of a foam layer at the 357 358 reservoir roof, or by processes of magma mixing occurring within the magma chamber (e.g., Harris and Neri 2002, Lautze et al., 2004). However, in the case of Holuhraun eruption, the link between the 359 effusive trend and the collapse of the caldera (Fig. 3b) claims for a simple, gravity-driven dynamic 360 (Gudmundsson et al., 2016; Coppola et al., 2017) that would exclude, or minimize, the occurrence of 361 above mentioned processes. Hence, the TADR's pattern overprinted to the exponential trend is likely 362 related to the emplacement dynamic occurred during the course of the eruption, and especially during 363 the phases 1 and 2. Laboratory experiments (Garel et al., 2012, 2014) and theoretical treatments 364 (Tarquini 2017), demonstrated that a constant effusion rate can actually produce pulses of the 365 366 radiative power (Fig. 4b) that reflect the non-equilibrium steady-state growth of compound lava flow fields. According to Tarquini (2017) each flow unit will advance until the thermal equilibrium will 367 be reached and the flow front stop. Hence, the system is resettled to give origin to a new flow unit. 368 369 This seems to be exactly the dynamic occurred during the emplacement of the Holuhraun lava field, in which each apparent TADR's pulse correlates with a phase of lengthening of a distinct flow unit. 370 371 Notably, the amplitude of the pulses decreased with time as the overall effusion rate declined, the 372 maximum length attained by the flow units reduced, and the emplacement style evolved from channel- to tube-fed (Fig. 4b). 373

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5. Evolving emplacement style, evolving thermal structure

In this section, we illustrate how the evolving emplacement style and the channel- to tube-fed transition affected the surface thermal structure of the Holuhraun's lava field. In particular, we used the temperature profiles (as the one shown in Fig. 1c) obtained from the MODIS image, in order to track the position of the active flow fronts and all the hot lava surfaces emerging along the principal flow path (from West to East). By stacking together all the W-E profiles the presence of active lavas (i.e. the vent(s), open-channel(s), breakout(s), flow front(s), etc.) appears as high-temperature features (pixels), whose intensity, contiguity and extension can be easily visualized as shown in Fig. 5a. We assumed that the position of the flow front is represented by the easternmost pixel having a brightness temperature (BT4) of 50°C higher than the background (white dashed line in Fig. 5a). Hence, the distance between this pixel and the one located over the active vent (Fig. 1b), provides a measurement of the active flow length at each satellite overpass (red line in Fig. 5b). Lava flow lengths measured on the field during the phases 1 and 2 (Flows no. 1 to 8) are also plotted for comparison (Fig. 5b).

This analysis indicates that during the phases 1 and 2, the active flow fronts were thermally connected 388 to the vents, through a high-radiating feature representing the open channels. On the other hand, since 389 December 2014 the reduction of lava discharge rate caused a marked shortening of the open channels, 390 although the lava field was still characterized by the presence of active lavas at the distal front(s). 391 392 Notably, between the two hot, active zones (i.e. open channels and flow front) there low-temperature zone corresponding to crusted and cooling lava surfaces (Fig. 5a). This is a clear thermal evidence 393 that since the beginning of the phase 3 the transport of lava occurred along a master tube system and 394 395 that the emplacement style started to be *tube-fed* dominated.



Figure 5. (a) Evolution of the along-path thermal structure of the Holuhraun lava flow. This plot is obtained by stacking together all the thermal profiles (max BT4 along each N-S line) as those illustrated in Fig. 1c. The white dashed line indicate the position of the active flow front (see the text for details); (b) Comparison between measured (red dashed line) and modelled (blue line) flow length. The Calvari & Pinkerton's model (eq. 7) assumes emplacement style dominated by *channel-fed*, cooling limited conditions. The discrepancy between measured and modelled flow distance after December 2014 outline the increasing efficiency of *tube-fed* emplacement style in transporting the lava to the flow front.

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As a pure theoretical exercise, the flow extension measured by using the temperature profiles has been compared (Fig. 5b) with the maximum distance (L_{max}) predicted by one of the simplest empirical model developed for single, cooling-limited, channel-fed lava flow (cf. Walker 1973; Harris and Rowland, 2009). In particular, we used the Calvari and Pinkerton's equation (1998) that takes into account exclusively the *TADRs* measurements for the estimation of flow length:

410
$$L_{\rm max} = 10^{3.11} \times (TADR)^{0.47}$$
 (eq.7)

The coefficients of equation 7 were empirically determined by regression analysis of single channel-411 fed Etnean lava flows lasting 1 to 12 days, a duration very similar to the single flow units observed 412 at Holuhraun. This model does not require any knowledge of several others parameters (i.e. 413 underlying slope, lava temperature, viscosity, velocity, channel width, channel depth, etc...) that are 414 necessary to predict flow length using other approaches (see Harris and Rowland 2009 for a review), 415 but that are difficult, if not impossible to be constrained for each flow unit. However, despite its 416 simplicity, this empirical model of Calvari and Pinkerton 1998 allows to calculate the maximum 417 length of the Holuhraun's lava flow, and to see the effects of an emplacement style persistently 418 dominated by channel-fed, cooling-limited conditions (blue line in Fig. 5b). 419

During the phases 1 and 2, there is an excellent correlation between the measured and the modelled flow lengths, both in terms of absolute values and pattern (Fig. 5b). This corroborate the fact that during this period the emplacement style was effectively those for which eq.7 was proposed to describe, that is single, channel-fed flows. Differently, since December 2014, there is a growing discrepancy between the measured and modelled flow length (Fig. 5b), exactly in correspondence of the formation of a master lava tube, as observed in the field (Pedersen et al., 2017).

From this picture, it is clear that the lower discharge rates characterizing the Phase 3, did not affect the maximum extent of the lava flow, still reaching a distance of more than 15 km, just before the end of the eruption (Fig. 5b). By paraphrasing Harris and Rowland, (2009) "the transition from poorly insulated (*channel-fed*) to well insulated (*tube-fed*) regimes increases the length that a lava flow can extend for a given *TADR*".

Notably, we may calculate the radiant density ($c_{rad} = VRE/Vol$) typical of the tube-fed flow field, by dividing the thermal energy measured during the Phase 3 ($VRE = \sim 0.4 \times 10^{17}$ J; Fig. 2b) by the volume lava erupted in the same time window, derived from Tandem-X measurements ($Vol = 2.6 \times$ 10^8 m³; Fig. 3a; Dirscherl and Rossi 2018). The resulting radiant density ($c_{rad} = \sim 1.5 \times 10^8$ J m⁻³) is only slightly higher than the radiant density calculated in the same way for the bulk channel-fed flow field emplaced during phases 1 and 2 ($c_{rad} = \sim 1.1 \times 10^8$ J m⁻³). This suggests that the variation of the

emplacement style produces an uncertainty in the TADRs measurement that does not exceed 30%, 437 when provided in near real time. In other words, our results point out that, the formation of a lava 438 tube does not affect substantially the amount of "active" lava radiating to the atmosphere, but simply 439 "made this lava to be transported further from the vent". The lava tube thus act as a simple extension 440 of the volcanic conduit, by displacing the vent downstream, likely along the main axis of the 441 previously formed flow units. The recognition of this behavior in near real time allow to update the 442 443 vent location and has been proved to be a necessary improvement to correct estimation of the lava flow path and the effective runout distance (Harris et al., 2018, this issue). 444

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446 6. Operational use of MIROVA system during the effusive crisis

By the end of November 2014, MIROVA started to be part of the monitoring system operative at the 447 448 Icelandic Meteorological Office (IMO) with the coverage of nine active volcanic systems. IMO is the main institution in Iceland in charge of monitoring natural hazards and issuing forecast and warnings 449 in case of impending or on-going eruptions. It operates a multi-sensors network that includes 450 seismometers, GPS and gas sensors for the geophysical monitoring. During the Holuhraun eruption, 451 gas monitoring activity was improved and new instrumentations were deployed and maintained at the 452 eruption site for the entire duration of the event (Pfeffer et al. 2017). The MIROVA system showed 453 its strength and reliability in a period of the year when, in Iceland, the day light time is very short. 454 455 Several of the instrumentations and products that could normally be used to monitor an eruption, 456 started to fail or to give incomplete data sets due to harsh weather conditions and limited sunlight. 457 MIROVA provided a robust and continuous data set on a daily basis which was used from November to March to follow the health and strength of the eruption, as well as the post-eruption phase. 458

On the operative side this system is revealed to be an important monitoring tool for following the temporal evolution of the eruption and providing estimates of the erupted lava volume in near real time (Coppola et al., 2017). Extrapolation of the effusive trend during the ongoing eruption may in

fact be used to forecast total erupted lava volume, which in turn is fundamental to drive some lava 462 flow modelling (i.e. Tarquini et al., 2018). Also, the recognition of emplacement style through the 463 analysis of flow' surface thermal structure (i.e. channel- or tube-fed lava flows) can be used to update 464 the position of active flow fronts, and to choose the appropriate modeling strategy, by tuning some 465 appropriate parameters that govern lava flow simulation's codes (i.e. Tarquini et al., 2018, this issue). 466 Most importantly the thermal data have proved to be very important for constraining the time of the 467 eruption end. A drastic change of TADR was observed since the end of January 2015 becoming clear 468 the second week of February 2015 (Fig. 4a). This change was interpreted by Coppola et al. (2017) as 469 due to the gradual closure of the magma path (dike) and indicated the potential timing of the end of 470 the eruption in guite a good advance, about one month before the declaration of ceased eruption. 471 These data were discussed within the Scientific Board Management meetings that were held from the 472 beginning of the eruption in collaboration with the Icelandic Civil Protection and the University of 473 Iceland. The very low TADR detected on 26 February 2017 (0.2 m³ s⁻¹; Fig. 4a), supported the 474 decision for a field crew to flight over the eruptive site on February 27 and declare that the eruption 475 476 was over.

477 The thermal data were useful for providing a semi-quantitative indication of the strength of the gas source affecting the ground level concentration (Simmons et al., 2017). Due to its extension the lava 478 field itself was a considerable source of volcanic gases. In addition, the gas released close to the 479 surface was more easily trapped within the boundary layer and largely affected the concentration at 480 ground. This fact suggested that the MIROVA detection and the VRP temporal variation could be 481 correlated with the amount of gases released at the source. In this way the VRP data have been used 482 by the forecasters at IMO to identify, in a qualitative way, when to expect an increase in the SO₂ 483 values in areas located downwind the eruption site. 484

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487 **7.** Conclusions

During the 2014-2015 Bárðarbunga-Holuhraun eruptive crisis, one of the main challenge for the volcanological community was to monitor the effusive process in a safely, timely and routinely manner. For the whole duration of the eruption, MIROVA provided a robust and continuous set of thermal data that were used to depict the effusive trend and to estimates the erupted lava volume although the changing emplacement conditions (from channel- to tube-fed flow) introduced uncertainties in the interpretation of the data.

The retrospective analysis of this eruption provides an exceptional opportunity to study the 494 relationship between heat flux and TADR during the emplacement of a large compound lava field. 495 We show that the overall trend of thermal emission was related to the combined effect of two over 496 497 imposed patterns: (i) a main exponential decay of the effusion rate trend, governed by the source processes and (ii) a secondary pulsating pattern related to the emplacement dynamic of the flow field. 498 We found that the magnitude and timing of these pulses were strictly related to the timing and length 499 500 scales of discrete flow units characterizing open-channel lava transport. Conversely, the formation of lava tubes produces smaller instabilities and promotes lava to flow at greater distance in steady-state 501 thermal conditions. This process is clearly visible from the evolution of the thermal structure depicted 502 from the MODIS-MIROVA images and allow to track changes in the lava transport mechanisms 503 operating during the eruption (Fig. 5a). The results presented here clearly indicate that the calculation 504 of erupted lava volumes from the integration of satellite-derived TADR allow to smooth the short-505 term perturbation associated to the emplacement dynamic and provide a robust way to depict source 506 eruptive trends. We thus regard the application of this methodology as a key-factor in volcano 507 508 monitoring and satellite-data-driven response to an effusive crisis (Harris et al., 2018).

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517 **References**

- Bonny, E., T. Thordarson, R. Wright, A. Höskuldsson, I. Jónsdóttir (2018) The volume of lava 518 erupted during the 2014 to 2015 eruption at Holuhraun, Iceland: A comparison between satellite 519 ground-based measurements, J Geophys Solid 123. and Res Earth, 520 https://doi.org/10.1029/2017JB015008. 521
- Calvari, S. and H. Pinkerton (1998) Formation of lava tubes and extensive flow field during the 1991–
 1993 eruption of Mount Etna, J. Geophys Res, B103, 27291–27301.
- Coppola, D., M. Laiolo, D. Piscopo and C. Cigolini (2013) Rheological control on the radiant density
 of active lava flows and domes, J. Volcanol. Geotherm. Res., 249, 39–48.
 doi:10.1016/j.jvolgeores.2012.09.005.C.
- 527 Coppola, D., M. Laiolo, C. Cigolini, D. Delle Donne and M. Ripepe (2016) Enhanced volcanic hot528 spot detection using MODIS IR data: Results from the MIROVA system, in Harris A. J. L., T.
- De Groeve, F. Garel and S. A. Carn (eds.) Detecting, Modelling, and Responding to Effusive
 Eruptions, Geological Society, London, Sp. Pub. 426, p. 181–205, doi:10.1144/SP426.5.
- Coppola, D., M. Ripepe, M. Laiolo and C. Cigolini (2017) Modelling Satellite-derived magma
 discharge to explain caldera collapse, Geology 45(6), 523-526. doi:10.1130/G38866.1.
- 533 Crisp, J. and S. Baloga (1990) A method for estimating eruption rates of planetary lava flows, Icarus,
 534 85(2), 512-515.
- 535 Crisp, J. and S. Baloga (1990) A model for lava flows with two thermal components, J. Geophys.
 536 Res., 95 (B2), 1255-1270.
- 537 Dirsherl, M. and C. Rossi (2018) Geomorphometric analysis of the 2014–2015 Bárðarbunga volcanic

538 eruption, Iceland, Remote Sens. Environ, 204, 244-259.

- Dragoni, M. and A. Tallarico (2009), Assumptions in the evaluation of lava effusion rates from heat
 radiation, Geophys. Res. Lett., 36, L08302. doi:10.1029/2009GL037411.
- Garel, F., E. Kaminski, S. Tait and A. Limare (2012) An experimental study of the surface thermal
 signature of hot subaerial isoviscous gravity currents: implications for thermal monitoring of
 lava flows and domes, J. Geophys. Res. 117:B02205. doi: 10.1029/2011JB008698.
- Garel, F., E. Kaminski, S. Tait and A. Limare (2014) An analogue study of the influence of
 solidification on the advance and surface thermal signature of lava flows, Earth Planet. Sci.
 Lett., 396, 46–55.
- Garel, F., E. Kaminski, S. Tait and A. Limare (2015) A fluid dynamics perspective on the
 interpretation of the surface thermal signal of lava flows, , in Harris A. J. L. , T. De Groeve, F.
 Garel and S. A. Carn (eds.) Detecting, Modelling, and Responding to Effusive Eruptions,
 Geological Society, London, Sp. Pub. 426, 243-256.doi: 10.1144/SP426.6
- Gíslason, S. R., G. Stefánsdóttir, M. A. Pfeffer, S. Barsotti, Th. Jóhannsson, I.Galeczka, E. Bali, O.
 Sigmarsson, A. Stefánsson, N. S. Keller, A. Sigurdsson, B. Bergsson, B. Galle, V. C. Jacobo,
- 553 S. Arellano, A. Aiuppa, E. B. Jónasdóttir, E. S. Eiríksdóttir, S. Jakobsson, G. H. Guðfinnsson,
- 554 S. A. Halldórsson, H. Gunnarsson, B. Haddadi, I. Jónsdóttir, Th. Thordarson, M. Riishuus, Th.
- Högnadóttir, T. Dürig, G. B. M. Pedersen, A. Höskuldsson and M. T. Gudmundsson (2015)
- Environmental pressure from the 2014–15 eruption of Bárðarbunga volcano, Iceland,
 Geochem. Persp. Lett., 1, 84-93.
- Gudmundsson, A., N. Lecoeur, N. Mohajeri and T. Thordarson (2014) Dike emplacement at
 Bárðarbunga, Iceland, induces unusual stress changes, caldera deformation, and earthquakes,
 Bull. Volcanol., 76, 869–875. doi:10.1007/s00445-014-0869-8.
- Gudmundsson, M. T., K. Jónsdóttir, A. Hooper, E. P. Holohan, S. A. Halldórsson, B. G. Ófeigsson,
- 562 S. Cesca, K. S. Vogfjörd, F. Sigmundsson, T. Högnadóttir, P. Einarsson, O. Sigmarsson, A. H.
- Jarosch, K. Jónasson, E. Magnússon, S. Hreinsdóttir, M. Bagnardi, M. M. Parks, V.

564	Hjörleifsdóttir, F. Pálsson, T. R. Walter, M. P. Schöpfer, S. Heimann, H. Reynolds, S. Dumont,
565	E. Bali, G. H. Gudfinnsson, T. Dahm, M. J. Roberts, M. Hensch, J. M. Belart, K. Spaans, S.
566	Jakobsson, G. B. Gudmundsson, H. M. Fridriksdóttir, V. Drouin, T. Dürig, G. Aðalgeirsdóttir,
567	M. S. Riishuus, G. B. Pedersen, T. van Boeckel, B. Oddsson, M. A. Pfeffer, S. Barsotti, B.
568	Bergsson, A. Donovan, M. R. Burton, A. Aiuppa (2016) Gradual caldera collapse at
569	Bárdarbunga volcano, Iceland, regulated by lateral magma outflow, Science, 353.
570	doi:10.1126/science.aaf8988.
571	Harris, A. J. L. and M. Neri (2002) Volumetric observations during paroxysmal eruptions at Mount
572	Etna: Pressurized drainage of a shallow chamber or pulsed supply?, J. Volcanol. Geotherm.
573	Res., 116, 79–95, doi:10.1016/S0377-0273(02)00212-3.
574	Harris, A. J. L. and S. Baloga (2009) Lava discharge rates from satellite-measured heat flux, Geophys.
575	Res. Lett., 36, L19302. doi:10.1029/2009GL039717.
576	Harris, A. J. L. and S. K. Rowland (2009) Effusion rate controls on lava flow length and the role of
577	heat loss; a review, in Thordarson, T., S. Self, G. Larsen, S. K. Rowland and A. Hoskuldsson
578	(eds) Studies in Volcanology: The Legacy of George Walker. Geological Society, London Sp.
579	Pub. of IAVCEI, 2, 33–51.

- Harris, A. J. L., S. Blake, D. A. Rothery, and N. F. Stevens (1997) A chronology of the 1991 to 1993
 Etna eruption using AVHRR data: Implications for real time thermal volcano monitoring, J.
 Geophys. Res., 102(B4), 7985–8003, doi:10.1029/96JB03388.
- Harris, A. J. L., J. Dehn, and S. Calvari (2007) Lava effusion rate definition and measurement: A
 review, Bull. Volcanol., 70, 1–22. doi:10.100 7/s00445-007-0120-y.
- Harris, A. J. L., S. Carn, J. Dehn, C. Del Negro, G. Guðmundsson, B. Cordonnier, T. Barnie, S.
- 586 Calvari, T. Catry, T. de Groeve, D. Coppola, A. Davies, M. Favalli, E. Fujita, G. Ganci, F.
- 587 Garel, J. Kauahikaua, K. Kelfoun, V. Lombardo, G. Macedonio, J. Pacheco, M. Patrick, N.
- 588 Pergola, M. Ramsey, R. Rongo, K. Smith, S. Tarquini, T. Thordarson, N. Villenueve, P.
- 589 Webley, R. Wright and K. Zakzek (2016a) Conclusion: Recommendations and findings of the

- RED SEED working group, in Harris A. J. L., T. De Groeve, F. Garel and S. A. Carn (eds.)
 Detecting, Modelling, and Responding to Effusive Eruptions, Geological Society, London, Sp.
 Pub. 426, p. 567-648. doi:10.1144/SP426.11.
- Harris, A. J. L., T. De Groeve, S. Carn, F. Garel (2016b) Risk evaluation, detection and simulation
 during effusive eruption disasters, in Harris A. J. L., T. De Groeve, F. Garel and S. A. Carn
 (eds.) Detecting, Modelling, and Responding to Effusive Eruptions, Geological Society,

596 London, Sp. Pub. 426, p. 1-22. doi:10.1144/SP426.29.

- Harris, A. J. L., O.M. Chevrel, D. Coppola, M.S. Ramsey, A. Hrysiewicz, S. Thivet, N. Villeneuve,
 M. Favalli, A. Peltier, P. Kowalski, A Di Muro, J-L Froger, L. Gurioli (2018) Validation of
 an integrated satellite-data-driven response to an effusive crisis: 2 the April–May 2018 eruption
 of Piton de la Fournaise, Special Issue: MeMoVolc, Annals of Geophysics, (in press, this issue)
- Lautze, N. C., A. J. L. Harris, J. E. Bailey, M. Ripepe, S. Calvari, J. Dehn, S. Rowland, and K. Evans Jones (2004) Pulsed lava effusion at Mount Etna during 2001, J. Volcanol. Geotherm. Res.,
 137, 231–246. doi:10.1016/j. jvolgeores.2004.05.018
- Pedersen, G. B. M., A. Höskuldsson, T. Dürig, T. Thordarson, I. Jónsdóttir, M. S. Riishuus, B. V.
 Óskarsson, S. Dumont, E. Magnusson, M. T. Gudmundsson, F. Sigmundsson, V. J. P. B.
 Drouin, C. Gallagher, R. Askew, J. Gudnason, W. M. Moreland, P. Nikkola, H. I. Reynolds, J.
 Schmith and the IES eruption team (2017). Lava field evolution and emplacement dynamics of
 the 2014–2015 basaltic fissure eruption at Holuhraun, Iceland, J. Volcanol. Geotherm. Res.,
- 609 10.1016/j.jvolgeores.2017.02.027.
- Pfeffer, M. A., B. Bergsson; S. Barsotti; G. Stefánsdóttir; B. Galle, S. Arellano, V. Conde, A.
 Donovan, E. Ilyinskaya, M. Burton, A. Aiuppa, R. C. W. Whitty, I. C. Simmons, P. Arason, E.
- B. Jónasdóttir, N. S. Keller, R. F. Yeo, H. Arngrímsson, Þ. Jóhannsson, M. K. Butwin, R. A.
- Askew, S. Dumont, S. von Löwis, Þ. Ingvarsson, A. La Spina, H. Thomas, F. Prata, F. Grassa,
- G. Giudice, A. Stefánsson, F. Marzano, M. Montopoli and L. Mereu (2017) Ground-Based
- 615 Measurements of the 2014–2015 Holuhraun Volcanic Cloud (Iceland), Geosciences, 8, 29.

- Pieri, D. and S. M. Baloga (1986) Eruption rate, area, and length relationships for some Hawaiian
 lava flows, J. Volcanol. Geotherm. Res., 30 (1), 29-45.
- Ramsey, M. and A. J. L. Harris (2013) Volcanology 2020: How will thermal remote sensing of
 volcanic surface activity evolve over the next decade? J. Volcanol. Geotherm. Res., 249, 217233.
- 621 Sigmundsson, F., A. Hooper, S. Hreinsdóttir, K. S. Vogfjörd, B. G. Ófeigsson, E. R. Heimisson, S.
 622 Dumont, M. Parks, K. Spaans, G. B. Gudmundsson, V. Drouin, T. Árnadóttir, K. Jónsdóttir, M.
- 623 T. Gudmundsson, T. Högnadóttir, H. M. Fridriksdóttir, M. Hensch, P. Einarsson, E.
- Magnússon, S. Samsonov, B. Brandsdóttir, R. S. White, T. Ágústsdóttir, T. Greenfield, R. G.
- Green, A. R. Hjartardóttir, R. Pedersen, R. A. Bennett, H. Geirsson, P. C. La Femina, H.
- Björnsson, F. Pálsson, E. Sturkell, C. J. Bean, M. Möllhoff, A. K. Braiden and E. P. S. Eibl
- 627 (2015) Segmented lateral dyke growth in a rifting event at Bárðarbunga volcanic system,
 628 Iceland, Nature, 517, 191–195.
- Sigurðsson, H. and R. S. J. Sparks (1978) Rifting episode in North Iceland in 1874–1875 and the
 eruptions of Askja and Sveinagja, Bull. Volcanol., 41, 149–167.
- Simmons, I, M. A. Pfeffer, E. Calder, B. Galle, S. Arellano, D. Coppola and S. Barsotti (2017)
 Extended SO₂ outgassing from the 2014-2015 Holuhraun lava flow field, Iceland, Bull.
 Volcanol., X. DOI: 10.1007/s00445-017-1160-6.
- Tarquini, S. (2017) A review of mass and energy flow through a lava flow system: insights provided
 from a non-equilibrium perspective, Bull. Volcanol., 79, 64. <u>https://doi.org/10.1007/s00445-</u>
 017-1145-5.
- 637 Tarquini, S., M. de' Michieli Vitturi, E. Jensen, G. Pedersen, S. Barsotti, D. Coppola, M. A. Pfeffer
- 638 (2018) Modeling lava flow propagation over a flat landscape by using MrLavaLoba: the case
- 639 of the 2014–2015 eruption at Holuhraun, Iceland, Special Issue: MeMoVolc, Annals of
- 640 Geophysics, 61. https://doi.org/10.4401/ag-7812.

- Walker, G. P. L. (1973) Lengths of lava flows. Philosophical Transactions of the Royal Society,
 London, 274, 107–118.
- Wooster, M. J., B. Zhukov and D. Oertel (2003) Fire radiative energy for quantitative study of
 biomass burning: derivation from the BIRD experimental satellite and comparison to MODIS
 fire products, Remote Sens. Environ., 86, 83–107. http://dx.doi.org/ 10.1016/S00344257(03)00070-1.
- Wright, R., S. Blake, A. J. L. Harris, and D. Rothery (2001) A simple explana-tion for the spacebased calculation of lava eruptions rates, Earth Planet. Sci. Lett., 192, 223 233.
 doi:10.1016/S0012-821X(01)00443-5.