The 2004-05 Mt. Etna compound lava flow field: a retrospective analysis by combining remote and field methods

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Key Points:

- New photogrammetric methods have shifted the paradigm of photogrammetry and are able to reduce the cost of volcanic monitoring.
- A decreasing front velocity that follows a power law characterizes the initial stages of lava field formation.
- Syn-eruptive DEMs acquisition improves our understanding of the emplacement dynamics of complex lava fields.

Abstract

Mapping lava flows frequently during effusive eruptions provides crucial parameters to better understand their dynamics, in turn improving our ability to model lava flow behaviour. New photogrammetric methods have recently been developed, shifting the paradigm of photogrammetry from pure method to a multidisciplinary approach able to reduce the cost of volcanic monitoring and widen the potential spectrum of application. In this work, we demonstrate how multi-view and single-view photogrammetry methods can be used effectively to extract accurate quantitative information from photographs taken during routine surveys over an active lava flow. One intriguing advantage of these methods is that they can re-use images acquired previously to extract new data from past eruptions. In particular, we reconstructed quantitatively the evolution of the lava flow field emplaced during 2004-05 at Mt. Etna, subdivided in five eruptive phases from the earliest simple lava flows to the final compound lava field about six months later. Our results show that, in the first week of eruption, lava field formation was characterized by an increasing lava length that followed a power law growth and by a decreasing front velocity that followed a power law as well. Thereafter, the length increasing became almost constant until the developed lava tube system was able to drain the lava for long distances, with the area inundated by lava that grew linearly in the first 20 days. Finally, we demonstrate the crucial role that the syn-eruptive DEMs acquisition could have to improve our understanding of the emplacement dynamics of complex lava fields.

1. Introduction

Mt. Etna, in Sicily (Fig. 1a), is an open conduit basaltic volcano characterized by frequent eruptive activity commonly ranging from lava fountaining to pure lava effusion (e.g. Andronico and Lodato, 2005; Branca and Del Carlo, 2005; Andronico et al., 2013). The eruptive activity may occur at the volcano summit or at the volcano flanks, with the lava flows in recent decades emplacing mainly on the southern and eastern flanks (e.g. Allard et al., 2006). Although the eruptive fissures/vents of the most recent activity opened at high elevations (e.g. the 2001 and 2002-2003 eruptions; Andronico et al., 2005a; Coltelli et al., 2007) or from the summit craters (Behncke et al., 2014; De Beni et al., 2015), lava flows have threatened the villages at the volcano foot more than once (e.g. Barberi et al., 1993; Andronico and Lodato 2005; Branca and Del Carlo 2005), as well as reached and destroyed tourist facilities (e.g. Andronico et al., 2005a). With more than fifty lava fountaining episodes producing highly-fed effusive activity after 2011 and about one million people living on its flanks (e.g. Andronico et al., 2015a; De Beni et al., 2015), Etna and its surroundings are among the inhabited areas with the highest risk of being affected by lava flows in the world. Although lava flows are unlikely to cause human fatalities, effusive eruptions may constitute a serious threat to infrastructure and property.

Real-time, continuous monitoring of active lava flows during eruption crises is one of the primary objectives of any volcano observatory, being crucial for civil protection purposes and volcanic risk mitigation. Daily surveys are fundamental to map the surface propagation of fracture systems and eruptive fissures, the evolution of lava flow fields over time as well as to infer the areas covered by lava flows and the advance rate of flow fronts. Moreover, field/ground observations allow tracking the formation and path of lava tubes, which is of particular interest because they promote lengthening of lava flow fields and consequently increase the potential hazard to villages on the slopes of the volcano (e.g. Calvari and Pinkerton, 1998, 1999; Kauahikaua et al., 2003).

Insights into the dynamics of lava flow emplacement and determination of the main relations between volume flux, rheology, channel geometry and ensuing fluid dynamics can be gained through numerical and empirical modeling. The length of lava flows has been related to viscosity (Nichols, 1939), eruption rate (Walker, 1973), heat loss (Danes, 1972) and erupted volume (Malin, 1980). Lava flows have also been modeled as Bingham fluids (Park and Iversen, 1984; Dragoni et al., 1986; Miyamoto and Sasaki, 1997; Harris and Rowland, 2001; Vicari et al., 2009). A number of interrelated factors are pivotal for determining the relations used in these models. Such factors include the erupted volume flux of lava (effusion rate), magma type, rheology, heat loss, cooling rate (and degree of thermal insulation), flow velocity, emplacement duration, slope and topography. However, these parameters of actual lava flows to be used as benchmarks and/or initial and boundary conditions for lava flow modeling are still lacking in number and accuracy (Tarquini et al, 2012a; Lev and James, 2014).

Consolidated methods are used to map the emplacement of active lava flows on Mt. Etna, among which ground-based surveys (Frazzetta e Romano, 1984; Calvari et al., 1994; Spampinato et al., 2011), aerial and satellite images (Coltelli et al., 2007; Del Negro et al., 2016; Ganci et al., 2018), airborne and terrestrial laser scanning (James et al., 2009; Favalli et al., 2009, 2010; Behncke et al., 2016). Recently, the use of photogrammetric computer vision techniques has been accepted for reconstructing and mapping the topography of a volcano, starting from photographs taken using a consumer-grade camera (e.g. Neri et al., 2017; Favalli et al., 2018; De Beni et al., 2019; Wakeford et al., 2019; Biass et al., 2019; Anderson et al., 2019; James et al., 2020; De Beni et al., 2020). Moreover, one of the most relevant advantages in using new photogrammetric methods is that they can be used to extract new information and data from images acquired in the past, when these methods and algorithms did not exist. In this work, single-view and multi-view photogrammetric methods are described and applied to acquire new data on the evolution of the lava flow field produced during the Etna 2004-05 eruption. Optical and thermal camera images acquired during this event have been elaborated using these methods in order to integrate the data with consolidated remote sensing technologies.

The long-lasting effusive eruption of 2004-05 of Mt. Etna (Fig. 1b) marked the resumption of flank activity after the 2002-03 eruption (e.g. Andronico et al., 2005a; Spampinato et al., 2008). The eruption, monitored by the Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo (INGV-OE), lasted six months, from 7 September 2004 to 8 March 2005, and was characterised by prolonged lava effusion discharged slowly by a fissure system that developed downward from the South-East Crater (SEC). The 2004-05 activity was characterized by an unusual onset if compared with Etna’s previous effusive eruptions. No significant volcanic precursors in the hours immediately before the onset were recorded (Burton et al., 2005), and the eruption start was not preceded or accompanied by either geophysical signals (Di Grazia et al., 2006) or geochemical variations in the plume fluxes and composition (Burton et al., 2005). This volcano behavior suggested that the beginning of the eruption consisted of only passive drainage of residual and relatively degassed magma already residing within the SEC conduit, rather than the arrival of a new volatile-rich batch of magma (Burton et al., 2005; Corsaro and Miraglia, 2005).

The eruptive activity produced a voluminous and compound lava flow field that filled and significantly modified the morphology of the upper part of the Valle del Bove (VdB) depression in the eastern flank of the volcano (Fig. 1). Neri and Acocella (2006), using field methods, assessed a total volume of emitted lava of ~ 40 x 10^6 m^3; later Del Negro et al. (2016), by high-resolution DEMs comparison, calculated a volume of ~ 62 x 10^6 m^3. INGV-OE monitored the lava flow field evolution acquiring campaign data, thermal and optical images from field surveys and helicopter over-flights in order to: (i) map the active lava flows and update the daily development of the lava flow field, (ii) distinguish between the main lava flow field structures (such as lava tubes, ephemeral vents, skylights and tumuli) and their evolution over time, and (iii) measure lava flow field areas and thicknesses. Although these data were fundamental for prompt civil protection purposes and volcanic risk mitigation, they still fell short in accuracy since the images acquired by thermal and optical camera were not georeferenced and thus could not be analysed in a GIS environment.

Other effusive eruptions of Etna in the past have shown similar eruptive behavior to the 2004-05 eruption, in particular in 1975, 1983, 1991-93 and 1999. Among these four compound lava eruptions, the 1975 eruption occurred during a period without surveillance activity, but we know that mild spattering activity preceding the eruption was characterized by very low effusive rates. Only the 1983 and 1991-93 eruptions had similar precursors to each other (seismic swarms typical of flank eruptions preceding the opening of eruptive fissures in the upper flanks of Etna), while the 1999 eruption started following the last of a sequence of 22 lava fountaining episodes, culminating in the formation of long-lived eruptive fissures in the slopes of the SEC cone.

In this work, we extended the analysis of the previous studies (Mazzarini et al., 2005; Neri and Acocella 2006; Favalli et al., 2009; Wright et al., 2010; Tarquini and de Michieli Vitturi, 2014; Del Negro et al., 2016) providing data at higher temporal resolution. This allowed a better understanding of the eruptive dynamics of prolonged lava effusions, which are valuable for civil defence purposes. In detail, our data enabled: (1) investigation and measurement of the morpho-structural evolution of the lava field with unprecedented temporal and spatial details; (2) discrimination among the main phases of its emplacement; (3) high-quality estimation of erupted lava volumes and thicknesses emplaced during and after the eruption, as well as the average effusion rates; (4) estimation of advance rates of several flows throughout the eruption. Finally, we calculated the lava volume using only field methods and assessed its accuracy using the volume derived from LiDAR DEMs comparison.

2. Data acquisition and Methods

The 2004-05 lava field evolution was here reconstructed using technologies, data and methods spanning from remote to *on-situ* techniques, from active to passive sensors, from mono- to multi-view photogrammetry, from digital terrain modeling to GIS analysis. All data are shown in Table 1 and they are briefly summarized below:

- TINITALY DEM (Tarquini et al., 2007; 2012) was the only available pre-eruptive digital topography completely free from the 2004-05 deposits. It was used to calculate, by comparison with 2004 LiDAR DEM, the volume of the earlier flows. TINITALY DEM is a 10-m resolution DEM derived from the 1:10,000 scale numeric 1998 topographic map of the Provincia Regionale di Catania (Sicily), published in 1999;
- Single optical and thermal images collected during the eruption were elaborated following the principles of single-image photogrammetry using both Pic2Map QGIS plugin (Produit et al., 2016) and an implemented *ad-hoc* code to obtain orthorectified images of the lava during its emplacement. Orthorectified images were then analysed in a GIS environment to map the flows during their advancement;
- LiDAR data acquired soon after the onset of the eruption and after its end (i.e. on 16 September 2004 and 29 September 2005) were used to map and calculate lava volume, area and thickness;
- A set of optical and thermal images collected during the eruption was used to generate a 3D model and DEM of the lava field when it was active using multi-view photogrammetry methods. By comparing this DEM with the LiDAR-derived DEMs, syn-eruptive volumes emplacement were measured;
- Landsat and ASTER satellite images were acquired to map the evolution of the lava field when other data at higher spatial resolution were unavailable. Only images with less cloud cover were used. Landsat 5 Thematic Mapper (TM) and Landsat-7 Enhanced Thematic Mapper Plus (ETM+) data were downloaded from https://espa.cr.usgs.gov. RGB bands

with spatial resolution of 30 m were used. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) has 14 spectral bands. RGB bands with spatial resolution of 15 m were used. ASTER data were downloaded from http://ava.jpl.nasa.gov/.
- GPS data collected after the end of the eruption were used to calculate the volume from field data.

2.1 Single-image photogrammetry

During the 2004-05 crisis, INGV-OE monitored the evolution of Etna's lava flows by using data acquired from digital aerial-photos and Forward Looking InfraRed (FLIR) Systems thermal camera (Calvari et al., 2004, 2005, 2006; Burton at al., 2005). Despite the key importance for real-time lava hazard assessment and management, both thermal and optical images were not georeferenced, and hence they were used to map the evolution of lava flows and distinguish between effusive vents, active lava flows, lava tubes, ephemeral vents and tumuli, albeit with some degree of uncertainty in the measurements. In order to extract quantitative data from one or more images, it is mandatory to initially georeference them and then to visualise and elaborate these georeferenced images into a GIS environment.

Single-image photogrammetry (or orthorectification) is a method that can relate a single oblique and un-rectified aerial image to the DEM of the corresponding real world. The image and the DEM are related to each other so that the camera centre, one selected point in the image plane, and the corresponding point in the DEM are collinear (Bozzini et al., 2012). To relate an image with the real word, the image must be accurately oriented in the space, namely the "camera pose" (position, orientation and scale factor) must be calculated. Single-image photogrammetry methods provide camera pose using as input a DEM and a set of ground control points (GCPs) identifiable both in the image (2D) and on a reference map with known elevation (3D), i.e. the DEM itself in our case (Fig. 2).

In this work, camera poses of thermal and optical (digital) images were assessed using the single-image photogrammetry method implemented in the Pic2Map QGIS Python Plugins (https://plugins.qgis.org/plugins/Pic2Map), which uses the 2D-3D correspondence between an image and the DEM to compute unknown parameters of the camera (Produit et al., 2016). The reference map we used was the 2004 LiDAR-derived DEM from which we also extracted the elevation data. GCPs were taken around the areas affected by the advancing lava flow (Fig. 2). The calculated geometry of camera acquisition was used to re-project the image to the real word by using an *ad-hoc* code.

Details on the optical and thermal images orthorectified for tracking the 2D evolution of 2004-05 lava flows are listed in Table 1.

2.2 Multi-view photogrammetry

On 18 February 2005, a helicopter survey, which was not conducted for acquiring photographs with the purposes of reconstructing the topography and so without any particular flight plan or pre-planned acquisition geometry, enabled collecting 110 thermal (404 × 240 pixels) and 153 optical images (3008 × 2440 pixels) with various overlap. This dataset was used to reconstruct the 2004-05 lava syn-eruptive DEM through Structure from Motion (SfM) methods.

The SfM method takes multi-view images as input data. Then, by combining advanced image feature detection and matching techniques, and a highly redundant bundle adjustment procedure, the 3D point cloud and camera orientations/poses are yielded in a common arbitrary 3D model coordinate system (Fig. 3). The point cloud generated from the SfM method is usually refined to a much finer resolution by using the Multi-View Stereo (MVS) method. Although the term SfM-MVS workflow would be more appropriate, it is common practice to refer to the system as SfM only. The 3D point cloud can then be appropriately scaled and oriented in a global coordinate reference system by applying a simple 3D similarity transformation (Westoby et al., 2012).

The general workflow we used to reconstruct the 3D scene geometry by the SfM method from a set of images with unknown interior and exterior orientation is described in detail in Kolzenburg et al. (2016) and Favalli et al. (2018). The final product of the SfM method was a 3D point cloud of the imaged surface with mean point density of 0.4 pt/m^2, which was used to generate a 4-m resolution DEM and an 0.2-m resolution orthophoto of the investigated area. The data set used in this work to generate a syn-eruptive DEM is listed in Table 1.

2.3 LiDAR high-resolution topographic data

The Airborne Light Detection And Ranging (LiDAR) system consists of several integrated technologies to collect, during a flight, a dense cloud of points with known coordinates representing the 3D model of the imaged surface. In brief, an airborne LiDAR system implements a remote sensing component and a georeferencing component. The remote sensing component is the LiDAR itself that includes the laser ranging and the laser scanning units. The georeferencing component is a position orientation system (POS), which includes a global positioning system (GPS) and an inertial measurement unit (IMU). The dense point cloud acquired using an airborne LiDAR system is used for generating a high-resolution digital elevation model (DEM) of the investigated surface (Wehr, 2009).

LiDAR data used in this work were acquired during two surveys over the summit area and the eastern flank of Mt. Etna carried out on 16 September 2004 and on 29-30 September 2005, respectively. At the time of the first acquisition, the 2004-05 eruption had been on-going for 9 days, while at the time of the second acquisition the eruption had ended ~7 months before; of note is that no relevant eruptive episode occurred between the end of the eruption and the second LiDAR acquisition. Since the LiDAR surveys were carried out at the very beginning of the eruption (the 2004 survey) and after the emplacement of the entire lava field (the 2005 survey), LiDAR data gave a snapshot of the lava field for only these specific times. The 2004 and 2005 LiDAR data sets used in this work were previously corrected for systematic errors as shown by Favalli et al. (2009), resulting in planimetric and vertical RMS errors of 0.55 and 0.16 m for the 2004 data and of 0.48 and 0.16 m for the 2005 data.

The point density of both LiDAR clouds is generally inhomogeneous and wide portions of the southern sector of VdB (which was partially buried by the 2004-05 lava flow) have no data points (Fig. 4). The point density is 0.42 pt/m^2 and 0.41 pt/m^2 for 2004 and 2005 data, respectively. In agreement with Behncke et al., (2016), a DEM with a resolution of 1 m was created from both LiDAR data sets. The LiDAR data set used in this work for generating syn- and post-eruptive DEMs is listed in Table 1.

2.4 GPS survey

On 7 June 2005, a GPS survey was carried out along a path crossing the 2004-05 lava flow field. Measurements were made in continuous kinematic mode using a Trimble 4700 double-frequency receiver controlled by a TSC1 hand module and equipped with a Trimble Zephyr geodetic L1/L2 antenna. Data acquisition (1 sec sync rate) started at 04:57 GMT with a static initialisation. After half an hour, the station started to rove until 14:00 GMT.

Data collected on 7 June and those recorded by the eight GPS stations of the Etna permanent network were processed together by using the 1.5 version of Trimble Geomatics Office package. In order to get a reference for the roving sampling, we used the GPS permanent stations, which collect data at 1 sec sampling rate. In this way, each point measured along the path (every epoch) was connected to eight reference stations. Precise ephemerides produced by the IGS (International GPS Service) and the antenna phase center calibration tables provided by the NGS (National Geodetic Survey) were introduced into the processing to improve the accuracy of the solution. In addition, in order to obtain better accuracy, several trials for processing the baselines were performed by sampling data at 1, 5, 10, 15 and 30 sec even if over a lesser number of points along the path. In fact, higher sampling rate often results in more noisy data that is considerably affected, for example, by multi-path effects and cycle slips, especially on the roving antenna due to the difficult path over the recent flows.

The best baseline solutions were obtained by processing the data recorded at a 30 sec sampling rate with a resulting mean Root Mean Square (RMS) error of 7-8 mm for the baselines solutions between every point along the path and every base station around, rarely exceeding 1 cm only for the longest baselines. Furthermore, due to the low speed of motion of the roving station over the flow field, the 30 sec sampling rate does not significantly reduce the spatial sampling of lava flows, resulting in a sampling point every 5-10 m for a total of 982 points along the roving path. Furthermore, due to the low speed of motion of the roving station over the flow field, the 30 sec sampling rate does not significantly reduce the spatial sampling of lava flows, resulting in a sampling point every 5-10 m for a total of 982 points along the roving path.

The nearly 7000 baseline solutions obtained were then analysed by network adjustment, performed in two steps. Firstly, the whole set of baseline solutions were adjusted according to the hypothesis of the inner constraints (the network has been fixed to its centroid) allowing data validation. Then, the network was fixed assuming an appropriate set of coordinates for the reference stations belonging to the permanent network. The final results of the adjustment were the 3D precise positions of the 982 points along the roving path. These were affected by a mean formal error of 6-10 mm for the horizontal coordinates and of 15-20 mm for the vertical one.

2.5 Quantitative analysis methods

The lava flow evolution was mapped by hand-digitizing lines from the aerial georeferenced images in a QGIS environment.

Volume, area and thickness of emplaced lava were calculated by DEMs subtraction according to the equation $V = \sum_i \Delta x^2 \Delta z_i$ (Favalli et al., 2010), where Δx is the grid step and Δz_i is the height variation at the grid cell *i*, i.e. the difference of the two grid values at the location *i*. The sum is of all the pixels inside the area where we wish to calculate the volume changes. Generally, the error on the volume assessment between DEMs is linearly dependent on the standard deviation on the height variations ($\sigma_{\Delta z}$) and it can be calculated using regions located around the area of interest, where the surface is considered not to have changed (i.e. control region) in the given time interval. Following Favalli et al. (2010) and similarly to Behncke et al. (2016) and Di Traglia et al. (2018, 2020), in this work we assumed that the matching errors between DEMs are completely correlated, thus we assigned to each pixel the maximum possible error, and we used the errors of the equation $\mathrm{Err}_{V,high} = A\sigma_{\Delta z}$, where A is the area across which we measured the volume changes.

We calculated the following DEMs differences: i) TINITALY and 2004 LiDAR DEMs differences for calculating the topographic changes induced by the emplacement of early flows; ii) 18/02/05 SfM-DEM and 2004 LiDAR-DEM comparison for calculating the topographic changes caused by the formation of a compound lava flow; iii) 2005 LiDAR-DEM and 18/02/05 SfM-DEM difference for calculating the topographic changes caused by the last effusive output before the end of the eruption; and iv) 2004 vs. 2005 LiDAR for calculating the (almost) final volume.

3 Temporal and spatial evolutions of the 2004-05 lava flow field

In the following, we have recognized five phases of the lava field evolution according to the opening of the different effusive vents, the propagation of single lava flows, and the development of the compound lava field accompanied by the formation of ephemeral vents, lava tubes, skylights and tumuli. The evolution of the eruption is summarized in the Supporting Information.

3.1 Phase 1 (7 September/Eruption onset - Mid-September 2004): fracture opening, effusive vent establishment and early flow advance

The first days of activity were marked by weakly fed lava effusion from Vent 0 (V_0 in Fig. 1b), by the opening of fractures along an ESE-trending fracture system (propagating from the eastern slope of the SEC towards VdB), by the establishment of the main effusive vents, i.e. Vent 1 and Vent 2 (V_1 and V_2 in Figs. 1b and 5), and the emission of the first flows. The 15 September 2004 LiDAR-derived DEM allowed to precisely collocate V_0 at an elevation of 2936 m, V_1 at 2640 m and V_2 at 2328 m above sea level (Fig. 1b). Hereafter, note that all elevations are above sea level to avoid repetition throughout the text.

Phase 1 was constantly monitored because of the good weather condition. This allowed us to reconstruct the evolution of the early flows in great detail. On the early morning of 7 September 2004, an eruptive fissure opened on the SEC eastern base at V_0: a weakly-fed lava flow, active for only a few hours, started and extended for about 280 m until an elevation of 2846 m covering a total area of 5.3×10^3 m^2, as measured on the 2004 LiDAR DEM (Fig. 1b). The effusive activity of V_0 was followed by the progressive development of an ESE trending dry-fracture system crossing the rim of the VdB western wall up to 2600 m.

On 10 September at 04:12 am GMT (GMT = local time – 2 hours; hereafter we refer only to GMT), a second effusive vent V_1 opened at 2640 m elevation in the western wall of the VdB. The new vent erupted a narrow lava flow that ran eastward crossing Serra Giannicola Piccola (SGP). On the same day, early in the morning, an aerial survey was performed over the lava flow highlighting the presence of two flows, with the longest reaching SGP (Fig. 5a). This georeferenced image acquired during the eruption allowed calculating that the total area invaded by the lava flow V_1 was 6×10^3 m^2, reaching SGP at an elevation of 2511 m with a maximum length of 237 m (Fig. 5a). For the sake of simplicity and coherently with Mazzarini et al. (2005) and Favalli et al. (2009), this flow was called Flow 1. The shortest branch emitted from V_1 was 127 m long and reached an elevation of 2566 m (Fig. 5a). Considering that V_1 opened around 04:12 am and that the photo, as recorded in the metadata, was taken at 07:40, in this time span, Flow 1 advanced with a mean velocity of 68 m/h. The area of the pit formed by V_1 was 0.2×10^3 m^2 (Fig. 5a).

On 11 September 2004 at about 05:30 am, the lava flow advance was acquired both by optical and thermal camera. Flow 1 reached an elevation of 2168 m. In about 22 hours, the lava front had run 591 m with a mean velocity of 27 m/h. The southern branch, not active during the survey, as revealed by the thermal camera, reached an elevation of 2449 m (Fig. 5b). The total area of the flow was 34×10^3 m^2. In the early afternoon of 13 September 2004, the third effusive vent V_2 opened at an elevation of 2328 m (Figs. 2 and 5c).

On 15 September 2004, aerial photographs acquired at 7:30 imaged Flow 1 emitted from V_1 and Flow 2 from V_2 (Fig. 5c). The front of Flow 1 moved downslope for 944 m, reaching an elevation of 1884 m with a mean velocity of 10 m/h. The total area covered by lava was 92×10^3 m^2. The flow from V_2 (Flow 2) was 841 m long and reached an elevation of 1980 m. Taking its opening time as early afternoon on 13 September, probably at around 12:00, the mean lava flow advance can be inferred as 20 m/h. The total area covered by lava was 16×10^3 m^2. 15 September aerial photographs show that vents V_1 and V_2 were feeding single aa lava units characterized by well-formed lava channels. At this time, Flow 1 did not have overflows. Moreover, the channel was well-developed and there was no evidence of lava breakout or dams at the overflow point described in Tarquini and de' Michieli Vitturi (2014), which they called "ω", a term that we use in this paper too. Tarquini and de' Michieli Vitturi (2014) inferred the time of lava overflow approximately between late 15 and early 16 September. Two different lava pulses can be distinguished in the channel, one upstream and one downstream. The fronts of the two lava pulses were 524 m away. The lower pulse was 210 m long. The channel was well-established with a width of about 18-20 m in the distal part of the flow. There is evidence of an old lobate front emplaced at an elevation of about 2000 m before 15 September (Fig. 5c). Flow 2 also had a well-formed channel with channel width ranging from 6 to 10 m.

On 16 September 2004, from 5:00 to 6:30 am, a LIDAR survey imaged the 2004-05 eruption (Mazzarini et al., 2005; Favalli et al., 2009). Compared to the position of the front on 15 September, the front of Flow 1 had advanced 121 m in 24 hours, corresponding to a mean velocity of 5 m/h, reaching an elevation of 1852 m close to Mt. Centenari for a total length of ~1.9 km (Fig. 5d). The total area covered by the lava emitted from V_1 was ~ 134×10^3 m^2. Flow 2 advanced 59 m in about 24 hours (mean velocity 2.5 m/h) down to 1968 m for a length of 900 m, forming a zone of dispersed flow with four main lobes. The total area covered by the lava emitted from V_2 was ~ 21×10^3 m^2. By comparing 2004 LiDAR survey and 1998 TINITALY DEM, we measured the volume changes only for the lava emitted from the V_1 in the interval between 7 and 16 September. The volume of the lava emitted from the V_2 was not calculated because this area was affected between the two DEMs acquisition times by the emplacement of products, mainly tephra, emitted during the 1999, 2001 and 2002-03 eruptions (e.g. Coltelli et al., 2007; Andronico et al., 2005). The lava emitted from V_1 caused a volume gain of ~$1.1 \pm 0.2 \times 10^6$ m^3 with an average thickness of 8.63 m and a mean effusion rate of about 2.1 m^3/s. This volume is the same inferred by Mazzarini et al. (2005) by using as pre-existing topography the interpolation of the topography at the edge of the flow. Comparing the extensive morphometric analysis made by these authors with the channel dimension measured in this work, it is clear that the channel width did not change significantly from 15 to 16 September.

Favalli et al. (2009) described a feeding system on 16 September organized in lava pulses, which were advancing downhill along the active channelized flow units. The lava mainly fed the overflow unit 1.2 (Flow 1.2, Fig. 5d), while flow unit 1 (downhill from the overflow point "ω") and overflow unit 1.1 (Flow 1.1, Fig. 5d) were not changing in thickness, being essentially inactive. The main pulses along Flow 1.2 travelled at 200 m/h, while the front 1.2 advanced 23 m in 76 minutes at an average speed of 18 m/h (Favalli et al. 2009). In addition to the overflow occurring in the night between 15 and 16 September, Favalli et al. (2009) also described a small overflow along the main channel 1.

As a whole, Phase 1 was characterized by the development of distinct lava flow units running within narrow lava channels. The overflow formation in Flow 1, dated to the night between 15 and 16 September (Tarquini and de' Michieli Vitturi, 2014), can be considered a prelude to the formation of a compound lava flow field and marked the beginning of Phase 2.

3.2 Phase 2 (Mid-September – end-September 2004): formation of the compound lava flow field

Starting from the night between 15 and 16 September, the effusive activity was characterised by overlaps and overflows of single lava flows, which led to the development of the compound lava flow field and growth of relative width and thickness.

On 20 September, an aerial survey was performed at about 06:00 am. Five fronts (named Flow 1.1 to 1.5) related to vent V_1 were recognizable, of which only Flow 1.5 resulted active, or abundantly fed, during the survey (Fig. 6a). In detail, a new branch (Flow 1.3, Fig. 6a), north of Flow 1, had been emplaced between 16 and 20 September and, at the time of the survey, halted at 1936 m. Flow 1.1 remained trapped between Flow 1 and Flow 1.3. South of Flow 1, there was also a new branch (Flow 1.4, Fig. 6a), which showed a large dispersed front. The front of Flow 1.2 reached 1703 m running for about ~1 km (Fig. 6a) with an average velocity of ~10 m/h (assuming that its front had not halted before). Next to Flow 1.2, Flow 1.5 reached 1767 m (Fig. 6a). The emplacement of Flow 1.5 front was driven by the presence of the distal part of Flow 1.2. The total area covered by the lava from V_1 was ~ 310 × 10^3 m^2. The flow from V_2 did not advance significantly but was affected by several overflows. The total area covered by the lava from V_2 was ~ 53 × 10^3 m^2.

On 22 September at about 7:00 am, Flow 1.5 reached an elevation of 1721 m and had partially surpassed the distal sector of the lava front of Flow 1.2 (Fig. 6b). In almost two days, Flow 1.5 advanced ~ 208 m with a mean advancing velocity of ~ 4.4 m/h. Flow 1.2 did not advance further. Flow 2 did not advance significantly but continued to expand as result of successive overflows (Fig. 6b).

On 23 September, a field survey was carried out a few minutes after 5:00 am using optical and thermal cameras. The georeferenced image acquired with the thermal camera clearly showed the complex structure of the field (Fig. 6c). The proximal areas of both lava fields, between vents and 2150 m, often developed lava tubes. The main lava tubes were directly connected to the main effusive vents. Lava started to roof in the proximal area propagating gradually down slope. Lava tubes were often characterized by a number of skylights, likely due to partial collapses of the tube roofs, and were elongated in line with the lava flow direction (Figs. 7c). Sometimes these skylights emitted lavas that formed a moustache-like shape (Figs. 7c), flowing along the sides of the tube (Calvari et al., 2005). The extrusion of lava through skylights might be associated with increases of effusion rate and the subsequent rising lava level within the tube. Alternatively, poor lava tube efficiency after the skylights may also form by incomplete sealing of the tube's roof.

In the V_1–fed field, only Flow 1.5 seemed to be supplied. The optical photo showed that the Flow 1.5 front advanced ~ 100 with a mean velocity of ~ 4.5 m/h, reaching 1691 m (Fig. 6c). The total area covered by the V_1–fed field was ~ 379 × 10^3 m^2. The total area covered by the V_2–fed field was ~ 122 × 10^3 m^2.

By 24 September at 7:30 am, V_1-fed lava flow field had a length of ~2.4 km reaching the base of the western VdB wall at 1678 m (Fig. 6d). The most advanced front fed by V_1 advanced ~140 m, keeping its mean velocity almost constant at around 5 m/h. The total area covered by the lava field was ~ 396 × 10^3 m^2. Vent V_2 had fed flows extending for maximum lengths of ~1.2 km, whose fronts had reached 1855 m elevation (Fig. 6d). The total area covered by the lava field was ~ 137 × 10^3 m^2.

After 24 September, the weather became increasingly worse and prevented frequent remote surveys of the area. Individual lava fields from the main vents may have merged in early October, to build up a single lava field downslope. This event marked the end of Phase 2 and the beginning of Phase 3.

3.3 Phase 3 (October 2004 – December 2004): Growth of the lava flow field and tumulus formation

From October on, the effusive scenario became complex due to the coalescence of the two lava flow fields developing down from V_1 and V_2, which resulted is a single compound lava flow field (Fig. 1b). After 1 and 2 October, a slight decrease in lava effusion from V_1 was observed during a field survey.

Despite the clouds, the Landsat 5 image of 1 October shows an enlargement of the V_2-fed field and possibly an overflow onto the V_1-fed field (Figs. 8a). On 7 October, lava flows emitted by ephemeral vents from V_2 were appeared to be confined between 2000 m close to SGG ridge and 1850 m elevation, as observed during a field survey. Following Calvari and Pinkerton (1998), the gradual formation of the compound lava field might be due to the establishment of stable lava tubes that drained lava through first-order ephemeral vents from high gradient zones. This assumption should also be depicted by the thermal image taken on 23 October (Figs. 7b inset) as well as inferred by the Landsat 7 image acquired on 25 October, where it is also clear that the V_2 front eventually reached the bottom of the VdB where the slope was gentle (Figs. 7b). The decrease of the slope gradient and the lower velocity of the advancing lava led to the front cooling and overflows (Calvari et al., 2002), while secondary branched fronts formed a large lava fan. Ephemeral vents (that opened mainly at the exit of the main lava tubes; see inset in Fig. 7b) fed short-lived lava flows that after almost a day cooled or roofed, developing ephemeral lava tubes of secondary order. This process produced a complex lava tube network. The Landsat 7 image of 25 October shows a significant advance of the front fed by the V_2 field (Fig. 7c). Comparing Landsat satellite images taken on 1 and 25 October, the V_2 lava flow front could have run for about 500 m, which would mean a velocity of about 1 m/h, reaching an altitude between 1680 and 1670 m.

Despite the low resolution, the Landsat 7 image acquired on 26 November, as described by Del Negro at al. (2016), shows a complex lava system, made up of different flows fed by several vents. The most advanced lava flow reached an altitude of about 1650 m. In the first weeks of December, no significant variations in the eruptive activity were reported, as shown in the thermal images of Figure 1 from Burton at al. (2005). During the following weeks, the lava flow field grew in terms of thickness and volume, especially where the presence of a break-in-slope permitted the formation of a number of second and third-order ephemeral vents (Calvari and Pinkerton, 1998), feeding lava units overlapping each other. These developed eventually into secondary lava tubes. In time, second and third-order ephemeral vents and secondary lava tubes built up a complex lava flow field spreading like a fan from the arterial tube exits. Here, two tumuli, T_1 and T_2 developed at the breaks-in-slope on the western wall of VdB. An optical photo taken on 19 December 2004 (Fig. 7c, inset) shows incandescent, active lava flows that characterize the distal zone of the lava flow field, in particular the area below the main VdB break-in-slope. In the proximal areas, lava flows ran within well-roofed lava tubes.

A Landsat 7 image taken on 28 December 2004 (Fig. 7d) allows to (roughly) fix the position of T_1 and T_2 at about 2170 and 1720 m, respectively, which corresponds approximately to the elevation of prominent break-in-slopes. At this stage, the lava flow reached elevation 1600 m, corresponding to the southeast branch of its final shape. The front had advanced since 26 November for about 800-900 meters, maintaining its flow velocity at about 1 m/h.

The starting of tumulus activity marked the end of phase 3 and the beginning of phase 4.

3.4 Phase 4 (January – mid February): Tumuli activity

Between Mid-January and the beginning of February 2005, lava effusion produced the widening of the lava flow field in the VdB. Activity centered at the top and lower base of the tumuli promoted lava flow field development in thickness and length. The two tumuli grew significantly both in elevation and width. Their development was triggered by the decrease in lava flow velocity at the tube exits (causing lava inflation and opening of ephemeral vents; Calvari and Pinkerton, 1998), and the accumulation and superimposition of countless short lava units (e.g. Duncan et al., 2002; Lodato et al., 2007). Further, the continuous lava flow output from ephemeral vents caused the gradual thickening of the lava field and its extension.

An ASTER image acquired on 4 January 2005 (Fig. 8a) shows T_1 at 2167 m while T_2 is not visible. With some degree of uncertainty due to the spatial resolution (i.e. pixel size 15 m), the lava field area measured on the image was about 1.9×10^6 m^2. This is the first measured area of the early compound field after the two initial separated fields merged together. Despite the low resolution, a Landsat 5 image acquired on 6 February shows that at this time the lava field almost reached its maximum length having reached 1474 m (Fig. 8b). Moreover, a lava flow from T_1 directed to the east and surrounded Mt. Centenari. Georeferenced thermal images acquired on 11 February, merged accurately, show that the activity had mainly concentrated on the two tumuli (Fig. 8c). Despite the low quality of the images in the proximal areas, it is possible to infer that the activity mainly consisted of the emission of short-lived lava flows.

After mid-February, the eruption diminished notably in terms of new emitted lava and thus lava flow field expansion.

3.5 Phase 5 (mid-February - 8 March 2005): Regression of the effusive activity up to its total exhaustion

Aerial and thermal georeferenced images acquired on 18 February show that the lava field was almost completed (Fig. 9a). The lava flow produced by T_1, detected on the 6 February Landsat image, surrounded Mt. Centenari cone. Lava overflows occurred from V_1, marking the poor efficiency of the lava tube system and the end of the effusive activity at T_1 (Fig. 9b). Only one flow, which almost reached SGG, is abundantly fed by V_1. T_2 shows a residual activity, producing short-lived lava flows that increase the thickness of the distal portion of the field. On 19 February, a few ephemeral vents on T_1 emitted small flows, while the only highly fed flow advanced about 380 m. On the same day, T_2 also seemed to have ceased its effusive activity (Fig. 9c).

Numerous photographs taken on 18 February allowed compiling a DEMs using the SfM method. Comparing the SfM-derived DEM and the LiDAR-derived DEM of September 2004, an emplaced lava volume of ~$54.5 \pm 3.22 \times 10^6$ m^3 is calculated in the relative time span (Fig. 10a). The $\sigma_{\Delta z}$ calculated using the areas outside the 2004-05 lava flow is 1.14 m. The maximum accumulation was recorded in the areas affected by tumulus activities, where the thickness of the 2004-05 lava was 81 m for T_1 and 78 m for T_2 (Fig. 10c). Although the eruption was almost at its end, an amount of lava still had to be emplaced.

In order to measure the amount of lava emitted during the last days of activity, we compared the 18 February 2005 SfM-derived DEM with the post-eruption LiDAR-derived DEM (Fig. 10b). Figure 10b shows that the lava flow field regressed with upward migration of the effusive activity. The gradual lava flow field closure enabled the development of overflows in the proximal area, confirming the poor efficiency of the arterial tubes, probably due to collapses and obstructions. The distal zone was characterized by ephemeral vents producing short, narrow lava flows, draining the residual magma within the tube networks. This activity produced a final further thickness increase (Fig. 10b). The $\sigma_{\Delta z}$ calculated using the areas outside the 2004-05 lava flow was 1.16 m. We estimate an emplaced volume of ~$7.5 \pm 3.3 \times 10^6$ m^3 in the last weeks of activity. In addition, the southernmost flow ends its run, eventually emplacing in the VdB. The effusive activity at both V_1 and V_2 systems decreased gradually from the end of February until the definitive cessation on 8 March 2005 as was observed during a field survey.

4. Topographic changes owing to the 2004-05 lava flow

Topographic changes obtained by subtracting 2005 and 2004 LiDAR-derived DEMs are shown in Figure 10c. Volume changes calculation using multi-temporal DEMs are often affected by errors due to mismatching in x, y and z between the same areas imaged by the different acquisitions. Error distributions outside the area affected by real changes do not have systematic behavior. As a consequence, local mismatching between DEMs has been considered negligible even considering the presence of the wide area with low point density in both the LiDAR data. The $\sigma_{\Delta z}$ calculated using the areas outside the 2004-05 lava flow is 0.67 m. The difference between the 2005 and 2004 LiDAR-DEMs shows a combined volume gain of ~$62.2 \pm 1.9 \times 10^6$ m^3 for an identified total area covered by volcanic products of ~2.8×10^6 m^2 and average thickness of 22 m. The maximum accumulation reached a thickness of 90 m in the proximal sector of the field, and 78 m in the distal sector of the field (Fig. 10c). Considering that the volume estimated for the early flow was ~1.1 ± 0.2

× 10^6 m^3, the volume assessed from DEMs comparison for the 2004-05 lava flow is 63.3±2.1 × 10^6 m^3. These data are slightly underestimated since they do not account for the products from the V_0 (actually negligible compared to the total estimated volume) and the early products of the V_2. This volume corresponds to a mean eruption rate of 4.21±0.14 m^3 s^{-1}.

5. Volume calculation using field based method

With the aim of assessing the reliability of the field method to calculate the lava volume, either in the case that 3D remote data are not available or for assessing the reliability of old measurements, we compared the volume calculated based only on a field ("classical") survey (e.g. calculated from the invaded area, extracted by drawing the lava on a topographic map based on an aerial survey, and the lava thickness measured on field, Burton et al. 2005; Neri and Acocella 2006) with the volume calculated from LiDAR-DEMs comparison.

To derive the total lava volume emitted by the main effusive vents (V_1 and V_2), we divided the lava flow field into six sectors according to similar morphological characteristics (Fig. 11). This subdivision was performed not only by visual observation during the monitoring activity and after the end of effusive eruption, but also by using GPS data acquired during a field survey after the end of eruption (Fig. 11). The post-processing of GPS data provided accurate cross-sections of the lava flow field (Fig. 11), which were used to constrain thicknesses across zones with marked morphological variations. Additionally, a number of lava thickness measurements were performed along the flow field margins by using a laser rangefinder with meter-long accuracy. For each sector, we calculated the minimum, maximum and mean volume according to different evaluations of lava thicknesses.

Sector 1 corresponds to the upper portion of the lava field on the western wall of VdB, which is characterized by uniform high gradient slopes (Fig. 11). The lava emplaced in this sector was almost totally erupted during the first month, with only a low contribution in terms of lava volume in the last 3 weeks of eruption/after 18 February (see Fig. 10b). For this portion of the lava flow field, where the main effusive vents and the main lava tubes were located, we calculated lava volumes ranging between 8.28 and 15.52 × 10^6 m^3. Sector 2 mostly corresponds to the area covered by T_1 (Fig. 11). This sector was the most affected by effusive activity (during the first month due to the emplacement of single lava flow units and then by the development of T_1) with respect to the other sectors, and thus it is the thickest portion of the lava field that includes the greatest volume of erupted lava. Here, we calculated lava volumes ranging between 17.78 and 39.13 × 10^6 m^3. Sector 3 is the frontal portion of the lava field located northward of Mt. Centenari (Fig. 11). This sector formed due to the juxtaposition of single lava flow units. The lava amount emplaced here is low ranging, between 0.97 and 2.92 × 10^6 m^3, with very low lava thicknesses. Sector 4 is located between the lower portion of SGG and Mt. Centenari at the main VdB break-in-slope, between the western wall and the valley (Fig. 11). In this sector, lava flows partially covered the top of SGG and in addition, it is here that T_2 began to form. On Sector 4, we estimated on the whole volumes between 12.42 and 20.70 × 10^6 m^3. Sector 5 lies within the valley floor and is formed by the superimposition of lava flow units coming from both tumulus bases (Fig. 11). For this sector, we calculated lava volumes between 4.51 and 8.02 × 10^6 m^3. Finally, Sector 6 corresponds to the frontal portion of the lava flow field emplaced within the VdB floor (Fig. 11). This sector consists mainly of the juxtaposition of single lava flow units (related to the post-January 2005 effusive activity) and shows the lowest amount of erupted lava volume with values ranging between 0.83 and 2.50 × 10^6 m^3.

Summing the lava volumes evaluated for the six sectors, we obtain the total lava volume emplaced during the 2004-05 eruption by the field survey (GPS measurements and field observations). This ranges between 44.80 and 88.79 × 10^6 m^3, with a mean value of 66.17 × 10^6 m^3 corresponding to a mean eruption rate of 4.25 m^3 s^{-1}.

6. Discussion

The 2004-05 Etna eruption was unusual due to the absence of significant volcanic precursors in the hours immediately before the onset. Indeed, it was not preceded or accompanied by either geophysical phenomena, such as ground deformations, seismic swarms or volcanic tremor increase (Di Grazia et al., 2006) or geochemical variations in the plume composition (Burton et al., 2005). Nevertheless, the 2004-05 Etna eruption was able to emit more than 60 million of cubic meters of lava, building a compound lava flow field characterized by the presence of ephemeral vents, lava tubes, skylights and tumuli and notably changing the morphology of the southern VdB.

Field measurements, airborne data and satellite observations, as well as single- and multi-view photogrammetry, allowed mapping the growth of the 2004-05 lava flow field in great detail and extracting some quantitative information, such as the lava volume and the temporal evolution of covered area, maximum length and mean front velocity (Fig. 12).

6.1. Comparison with previous works

The 2004-05 lava flow evolution was previously described by Del Negro at al. (2016), mainly based both on satellite data and INGV-OE reports. In Del Negro at al. (2016), whose purposes were other than the sole reconstruction of 2004-05 lava flow evolution, the accuracy of extracted data was influenced by the spatial and temporal resolution of the images, as well as by the presence of cloud decks that blocked satellite views. For example, in our work, between the first two satellite images used by Del Negro at al. (2016) (16 September 2004 – 26 November 2006), we extracted data with high temporal evolution, allowing us to describe, qualitatively and quantitatively, the first overflows (Figs. 6 and 7), the merge between the two fields (Figs. 7 and 8) and the changes in the front rate advancements (Fig. 12). Slight differences in the position of the vents between our work and those described in Del Negro at al. (2016) can be ascribed to the different data/methods used to map them. Conversely, the V_1 and V_2 lava field areas measured on 16 September by Del Negro at al. (2016) over the ALI image is considerably overestimated compared to our data, i.e. field V_1 is nearly twice (about 255×10^3 m^2 vs. 136×10^3 m^2), while field V_2 is more than five times larger (about 117×10^3 m^2 vs. 21×10^3 m^2). The maximum length reached by the two sub-lava flow fields appears instead rather underestimated, i.e. the V_1 and V_2 fields are 1893 m and 900 m long in our work and only 1338 m and 749 m in Del Negro at al. (2016). On the LANDSAT 7 images of 26 November and 28 December, we only did qualitative analysis because the data resolution prevented us from providing accurate data. As concerns the area of the final lava flow, this work, calculated from LiDAR data, and from Del Negro et al. (2016), calculated over the ALI image, both converge to about 2.8 – 2.9 × 10^6 m^2, while there are some differences in the final lowest altitude reached by the lava, in our case 1452 m vs. 1500 m estimated by Del Negro et al. (2016), and in the final maximum length, i.e. 4660 m vs. 4373 m, respectively. These differences can be ascribed to different data used for mapping as well as to the differences in the vertical datum used (in this work we used the geodetic height).

The 2004-05 lava flow evolution was qualitatively described by Burton et al., (2005), but they restricted their observation to the first three months of activity, until the end of November 2004. Burton et al., (2005) reported the area covered by the field (~0.79 km^2) and the lava length (~2.5 km). They also, by measuring on field the lava thicknesses, inferred a volume of 18.5-35 × 10^6 m^3 and a mean eruption rate of between of 2.3-4.1 m^3/s. The only data we extracted at the end of November is the maximum length, which was just under 3 km, i.e. a bit longer than the length measured by Burton et al., (2005).

The 2004-05 lava volume calculated in this work is $63.3 \pm 1.4 \times 10^6$ m^3. This volume matches the volume found by Del Negro at al. (2016) by comparing LiDAR-DEMs. The mean volume estimation calculated using only field methods is 66.17×10^6 m^3. These two data are fairly consistent. Considering the LiDAR volume as the ground truth, the mean lava volume inferred from field and GPS survey differs from it only by ~6%. Furthermore, this difference is slightly overestimated because the LiDAR volume does not take into account the products from the V_0 and the early products of the V_2. Our estimations by ground-based data are significantly higher than those from Neri and Acocella (2006) who calculated a total volume of ~ 40 x 10^6 m^3 of erupted lava with an estimated mean eruption rate of 2.0-2.5 m^3 s^{-1}.

6.2. Evolution of the main physical parameters with time

The temporal evolution of maximum length, area and front velocity of the field from V_1 in Phase 1 and 2 are reported in Figure 12. We described only the V_1-fed flows because the V_2 flow parameters can only be measured when they have reached a large flat area (Fig. 5 and Fig. 6) and, as consequence, we only observed a consistent area growth without any increase in length. In addition, only Phase 1 and Phase 2 were reported because they enabled collecting data with proper time resolution to reconstruct the evolution of the main parameters. Figure 12a shows that the length of lava flows grows, during Phase 1, as a power law with exponent of 0.506. During Phase 2, the increasing in length became almost negligible because the channel of Flow 1 was abandoned in favour of Flow 1.2, which gradually flanked Flow 1. Moreover, during Phase 2 the flows soon reached a large flat area where they started to spread, hence increasing their width rather than their length (cfr. Fig 5 and 7). The 2004-05 lava length evolution in its early stage had the same trend as other single flows from Etna (Fig. 12a), i.e. all of them show a growth that follows a power law but with different exponents. We can speculate that this difference can be ascribed in the first instance to the difference in the effusion rates, over 10 m^3/s for the 2001 (Behncke and Neri 2003) and 2002 (Andronico et al., 2005) lava flows, variable for 2006 lava flow (Vicari et al., 2009) and low for the 2004-05 early flow (about 2.1 m^3/s), where the higher effusion rate corresponds, as expected, to the higher flow capability of running long distances. However, a few days after the onset of the eruption, from 2 to about 6 days for the lavas represented in the Figure 12a, the dynamics of lava front and cooling seem to trigger the enlargement of the lava flow, which can then advance further either by changing direction/path or benefitting by thermal isolation of the channels and the lava tubes.

Figure 12b describes the behavior of the ratio between width and length (W/L) of the flow, which better illustrates the behavior of the lava flow during Phase 1 and 2. In particular, during Phase 1, W/L quickly decreased because only Flow 1 was flowing on a steep slope, reaching the minimum value at the end of this phase; thereafter, the ratio increased gently due to emplacement of new lava branches (Phase 2). This behavior is coherent with the theoretical curve described by Kilburn and Lopes (1988) representing the behavior of the ratio between lava width and length with time. Figure 12c shows that during Phase 1 and 2, the V_1–fed area increased linearly with time. Figure 12d shows the trend of velocity with time: the very high initial value of almost 70 m/h strongly decreased in the very first days following a power law with negative exponent of 0.494, afterwards the velocity stabilised between 4 and 5 m/h. This trend is also in good agreement with the initial opening of the vent system and early lava flow propagation (Phase 1), and the following emplacement of the compound lava flow field (Phase 2). A similar trend can be observed for the 1983 lava flow (Frazzetta and Romano 1985).

The transition between Phase 1 and Phase 2 marks the transition from simple to compound lava flows. Obviously, this a crucial moment in the lava field evolution, with relevant consequences also for hazard. To look deeply into this issue would require modeling the flow as was done by Tarquini and de Michieli Vitturi (2014) and Castruccio et al. (2014), which is beyond the scope of this paper. Nevertheless, it is possible to observe a similar length vs. time trend in the early stage of eruption between the 2004-05 Etna eruption (this work) and the 2002-03 Etna eruption (Castruccio et al., 2014). Since in our case the average supply rate can be considered almost constant in the first days of eruption (Tarquini and de Michieli Vitturi, 2014) and low (2.1 m^3/s), the variation of the rheology and topography with distance from the vent seems to play a major role in the transition between single flow to compound lava field.

6.3. Comparison with historical eruptions

The in-depth study of the 2004-05 eruption helped us define the development of the lava flow field and its parameterization. Indeed, aside the rheology properties of Etna's magmas, the final result of the 6-month-lava effusion, i.e. the complex lava flow field made by the variety of structures described in the previous sections, can be explained mainly by the combination of two dominant parameters: the rate of lava effusion and the topographic gradient of the slope. It is noteworthy the control of effusion rate in determining the kind of lava flow emplacement, lava flow dimensional properties (length, width, thickness, area, and volume), and the lava flow field final morphology (e.g., Harris et al., 2007; Harris and Rowland, 2009). In basaltic volcanic systems, high rates of lava effusion (especially during the first phases of vents/fissure opening or conduit breaching) have allowed fast drainage of lava that has reached long distances from the feeding craters/vents, mostly producing single lava flow units (e.g., Walker, 1972; Walker et al., 1973; Wadge, 1978; Wadge, 1981; Harris and Rowland, 2009). By contrast, low rates of lava supply have fed short lava flows that have reached small distances from the vents, and that have often overlapped or emplaced side-by-side developing compound lava fields (e.g., Walker, 1972; Walker et al., 1973; Wadge, 1978; Wadge, 1981; Harris and Rowland, 2009). For instance, during the 1975 eruption of Mt. Etna, Pinkerton and Sparks (1976) described the formation of a highly-compound lava flow field starting from an elevation of 2625 m, characterized by low effusion rates (0.5 m^3 s^{-1}) which were crucial towards form thousands of flow units (both 'a'a and pahoehoe) fed by a complex lava-tube network. These lava effusion rate values are comparable with those derived for the 2004-05 eruption, whose mean values were estimated at 2-4 m^3 s^{-1} during the first days following the eruption onset (Burton et al., 2005; Mazzarini et al., 2005; Harris et al., 2007), during which single lava units emplaced, and variably declining to low values < 1 m^3 s^{-1} in the phases during which the compound lava flow formed.

In 1983, Frazzetta and Romano (1985) and later Guest at al. (1987) described the development of another compound lava field at Mt. Etna. The 1983 eruption lasted 131 days, producing an inferred volume of $100 \pm 20 \times 10^6$ m^3 (Frazzetta and Romano 1985). The mean front velocities during the first days of the two eruptions are very similar: the 1983 eruption advanced at 70 m/h the first day and 20 m/h on the third; the 2004-05 eruption at 68 m/h the first day and 27 m/h on the second. In the 1983 field, lava tubes formed after the 62nd day, while probably between the 24th and the 47th day of activity in the 2004-05 field. Calvari et al. (1994) described the evolution of Mt. Etna's 1991-93 lava flow, a significant eruption that lasted 473 days and for which a lava volume of 235×10^6 m^3 has been estimated. Even in this case, the long-lasting effusive activity resulted in a compound complex lava field, whose development occurred according to five eruptive phases (Calvari et al., 1994). The first and second were the shortest and related to the emplacement of large aa flows accompanied by the development of lava tubes and ephemeral vents. The third phase was characterized by the emission of a very high number of pahoehoe flows and the formation of large tumuli structures, while the fourth phase was marked by the further expansion of the lava flow field. Finally, during the fifth phase the decreasing effusion rate caused the reduction of the lava emission in the upper portion of VdB. Despite important differences between the 2004-05 and 1991-93 eruptions, which included the building of a barrier to redirect the lava path (Barberi et al., 1993), a similar trend in the length and areal temporal evolution of the lava flow during the first phase of activity can be recognized. The mean average rate of lava lengthening of the 1991-93 eruption was 300 m/day, while in 2004-05 the lava reached 276 m/day; again, the areal rate of increasing was 0.11 km^2/day for the 1991-93 eruption and 0.21 km^2/day for the 2004-05 eruption. Finally, even during the 1999 eruption, which lasted 283 days, Etna supplied two large lava flow fields: the eastern and western ones (Calvari et al., 2002). The progression of the eastern lava flow field included features common to the 2004-05 event, consisting of the continuous formation of both small pahoehoe tongues and short aa flows caused by the development of a very complex lava-tube network, skylights, ephemeral vents and tumuli. After five days of eruption, the area covered by the 1999 lava was about 500 × 10^3 m^2 while the 2004-05 event in the same period covered an area of 92 × 10^3 m^2 (V_1). After 114 days of eruption, the area covered by 1999 lava was about 1.14 × 10^6 m^2, while after 119 days the 2004-05 area was 1.9 × 10^6 m^2. After about 2 and a half months, the 1999 eruption had developed the growth of many tumuli, while the presence of the 2004-05 tumuli was detected on 26 November, about three months after the onset.

Although the effusive events described here were characterized by different triggering mechanisms, it is possible to recognize similar features, such as long duration, phases of the lava flow field growth, formation, evolution and conclusion of lava-tube networks, ephemeral vents and tumuli. Indeed, looking at the possible causes that led to share comparable eruptive behaviors, in addition to the effusion rate control already discussed, the topography, and thus the change of the slope gradient, has surely played a major combined role. We believe, in fact, that topography (gentle slopes) and low effusion rates ($<5\ m^3\ s^{-1}$) characterizing these eruptions might explain such a common lava field morphological evolution. Calvari and Pinkerton (1998) widely discussed the relationship between magma supply rate at the sources and topography, particularly focusing on the development of lava field structures, such as lava tubes, ephemeral vents, skylights, and tumuli while investigating the 1991-93 eruption. Timely evidence has been provided by the 2008-09 eruption (Bonaccorso et al., 2011), which involved the north-eastern flank of VdB downward from 2700 m. On that occasion, in fact, tumuli formed in the middle, low-slope portion of the lava flow field (Calvari, 2009) at the exit of tube networks, and produced innumerable short flows characterized by low effusion rates. The effects of the variability of topography on lava flow field morphology have been recognized and detailed at other basaltic volcanoes such as Stromboli volcano (Aeolian Archipelago, Italy). Here during the 2002-03 effusive eruption, Calvari et al. (2005) and Lodato et al. (2007) described and discussed the development of a complex lava flow field that emplaced according to quite different topographies (low to high slope gradients), and which consequently was characterized by the formation of different field structures in different lava field portions.

7. Conclusion

Routine monitoring activity at Etna allowed collecting thermal and visual images during the six-month-long effusive activity occurring in the VdB depression between September 2004 and March 2005. Acquired data were not georeferenced and, consequently, quantitative analyses concerning the lava field evolution have been carried out with poor accuracy in the measurements. In brief, if an image cannot be displayed into a GIS, the observed phenomena cannot be measured with reasonable precision. In this work, we used recently introduced photogrammetric methods to extract qualitative data from thermal and optical images acquired during the 2004-05 eruption monitoring. Single-view and multi-view photogrammetric methods were effectively used for georeferencing thermal and optical images, providing data that integrated those acquired with consolidated remote sensing technologies (i.e. satellite and LiDAR data) and in the field. Single-view and multi-view photogrammetric methods gave new life to these images enabling higher accuracy, both in terms of spatial and temporal resolution, of the available data.

The 2004-05 compound lava flow formation was divided in five different phases. The evolution of the first two, i.e. the early advancing single flow and the start of the formation of the compound field, which lasted about 20 days, was quantitatively described with great detail both in terms of spatial and temporal resolution. The lava length increasing initially follows a power law as long as a single flow is being emplaced. With the establishing of the first lava branches, the maximum length became almost constant until the lava tube formation made the transport more efficient. The ratio width/length follows the theoretical behavior described in Kilburn and Lopes

(1988), which is the behaviour expected passing from a single to multi flows. The area covered by lava flows instead grows almost linearly, while the front advancing velocity decreases following a power law with negative exponent. Despite the paucity of data due to the bad weather conditions, the georeferenced thermal images, coupled with satellite images, allowed detecting other steps in the compound lava field evolution and describing them at least qualitatively. Particular relevant is the role of the tumuli, which formed at two main breaks in slope, proving crucial in the final expansion and growth of the lava flow field.

Despite the differences in the feeding systems, these data place the formation of 2004-05 lava flow field in the context of other compound lava fields where different eruptive phases can be recognized, characterized by a number of structures, such as ephemeral vents, lava tubes, skylights and tumuli, and for which it is possible to infer similar times of emplacement.

We demonstrate here that the spatial and the temporal resolution plays a crucial role in extracting quantitative data from images, in particular by measuring areas on low spatial resolution images can lead to serious errors in the area calculation, which, in turn, make these data unreliable when used to validate lava flow modeling. Moreover, we confirm that the most accurate method for calculating the lava volume is provided by the DEMs comparison. The field methods are also able to infer volume with acceptable accuracy, but only using technologies that can acquire high quality data such as differential GPS. However, field methods are very time consuming and require great effort in terms of human resources. We also demonstrate the crucial role that acquisition of syn-eruptive DEMs would have in understanding the compound lava field evolution.

Lava flow morphology depends on a complex interplay among different factors such as rheology, heat loss, topography and effusion rate. Most of the deterministic models that simulate that simulate lava flow advancement assumed Newtonian or Bingham rheology (e.g. Tallarico and Dragoni 2009; Del Negro et al., 2008; Fujita and Nagai, 2015). On the other hand, more complex models (Castruccio et al., 2010 and 2014) need a large set of parameters including morphometric ones such as the thickness and the widths of the flow. Castruccio et al. (2014) reconstructed the advancing of Etna's 2002-03 lava flow by extracting these parameters along the emplaced lava, assuming that they represented the dimension of the flow while it was moving. This assumption can lead to some errors, considering that more flows/plugs can follow the same path, and so it calls for measuring the lava morphometric parameters during the lava advancement. This can barely be done even using the recent technologies that allow extracting an accurate 3D model of the terrain (UAS and SfM methods, James et al., 2020). It goes without saying that morphometric data measured for old flows, either directly using the photographic archives or the maps or the reports, are considerably affected by errors (Castruccio et al., 2014). The technologies described here change this paradigm allowing one to accurately analyze the morphometry even of past lava flows.

The peculiarity of the 2004-05 eruption, which derives from the steady depressurization triggered by the continuous spreading of the volcano eastern flank, implies the possibility that effusive events with similar emplacement dynamics might reoccur in Valle del Bove in the future. In this framework, our results represent a useful contribution to the monitoring and understanding of lava flow evolution associated with unusual onsets of the eruption, such as the 2004-05 event, difficult to assess when not heralded by evident precursors

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Data Availability Statement

The data products generated in this study will be available on http://www.pi.ingv.it/banche-dati/ with the relative doi. They are temporarily uploaded as Supporting Information for review purposes.

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