Journal of Volcanology and Geothermal Research 204 (2011) 27–39

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Mapping and DOWNFLOW simulation of recent lava flow fields at Mount Etna

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ARTICLE INFO

Article history:
Received 28 January 2011
Accepted 1 May 2011
Available online 9 May 2011

Keywords:
LIDAR
lava flow field
lava flow simulation
Digital elevation model
Mount Etna

ABSTRACT

In recent years, progress in geographic information systems (GIS) and remote sensing techniques have allowed the mapping and studying of lava flows in unprecedented detail. A composite GIS technique is introduced to obtain high resolution boundaries of lava flow fields. This technique is mainly based on the processing of LIDAR-derived maps and digital elevation models (DEMs). The probabilistic code DOWNFLOW is then used to simulate eight large flow fields formed at Mount Etna in the last 25 years. Thanks to the collection of 6 DEMs representing Mount Etna at different times from 1986 to 2007, simulated outputs are obtained by running the DOWNFLOW code over pre-emplacement topographies. Simulation outputs are compared with the boundaries of the actual flow fields obtained here or derived from the existing literature. Although the selected fields formed in accordance with different emplacement mechanisms, flowed on different zones of the volcano over different topographies and were fed by different lava supplies of different durations, DOWNFLOW yields results close to the actual flow fields in all the cases considered. This outcome is noteworthy because DOWNFLOW has been applied by adopting a default calibration, without any specific tuning for the new cases considered here. This extensive testing proves that, if the pre-emplacement topography is available, DOWNFLOW yields a realistic simulation of a future lava flow based solely on a knowledge of the vent position. In comparison with deterministic codes, which require accurate knowledge of a large number of input parameters, DOWNFLOW turns out to be simple, fast and undemanding, proving to be ideal for systematic hazard and risk analyses.

1. Introduction

Mt. Etna is among the most active basaltic volcanoes of the world, and its effusive activity poses an incessant threat to human communities living on its flanks. This volcano is also one of the most studied in the world, and constitutes a natural laboratory where new techniques and tools contributing to advancements in volcanology have often been experimented (e.g. Wright et al., 2008a; Favalli et al., 2010).

Lava flow simulation is a front-edge technique which is increasingly used to mitigate the hazard posed by lava streams flowing downhill in populated areas (Crisci et al., 2003, 2010; Favalli et al., 2009a; Vicari et al., 2009; Favalli et al., Submitted). Mt. Etna has been one of the first natural scenarios where lava flow simulation codes have been tested and applied (Young and Wadge, 1990, Wadge et al., 1994). Since the early 1990s, at least 9 different lava flow simulation codes have been tested or extensively applied on this volcano: Dobran and Macedonio (Dobran and Macedonio, 1992), FLOWFRONT (Wadge et al., 1994), SCIARA (e.g. Crisci et al., 1999), LavaSIM (Hidaka et al., 2005; Proietti et al., 2009), DOWNFLOW (e.g. Favalli et al., 2005, 2009b), Costa and Macedonio (Costa and Macedonio, 2005a), ELFM (Damiani et al., 2006), FLOWGO (Harris and Rowland, 2001; Wright et al., 2008b), MAGFLOW (e.g. Vicari et al., 2007, 2009).

Existing lava flow simulation codes can be roughly classified in two broad categories: deterministic codes based on transport theory (e.g. SCIARA, Crisci et al., 2010), and probabilistic codes based on the maximum slope (e.g. DOWNFLOW, Favalli et al., 2005; see also Costa and Macedonio, 2005b). While deterministic codes are based on the solution of the physical governing equation of the flowing lava, and hence need the knowledge of a large number of input parameters (e.g. lava discharge rate, temperature, viscosity, etc.), probabilistic codes need only the calibration of a few parameters and they promptly yield results which are often representative of a wide spectrum of possible events.

The validation of the result of a lava flow simulation is obtained by comparing the area covered by the simulation output with the area covered by the corresponding actual lava flow (e.g. Vicari et al., 2007). An accurate mapping of real lava flows is therefore an essential element to assess the performances of a simulation code. Recently, LIDAR data processing proved to be a powerful technique for lava flow mapping (Mazzarini et al., 2007) and for the creation of high resolution digital elevation models (DEMs) of volcanic areas (Favalli et al., 2009c, 2010; Fornaciai et al., 2010).

In this work, we apply, at Mt Etna, a combination of different techniques to obtain enhanced maps of several recent lava flows based on LIDAR data processing (Mazzarini et al., 2007; Favalli et al.,

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doi:10.1016/j.jvolgeores.2011.05.001

2009c) and DEMs elaboration (Stevens et al., 1999; Neri et al., 2008). Afterwards, we use these maps, along with maps taken from existing literature, to validate the simulations of 8 recent lava flow fields obtained by using the DOWNFLOW code (Favalli et al., 2005). Selected fields, originating from flank and sub-terminal effusive activities with a vent opening at elevations from 1930 to 3230 m asl, erupted volumes ranging from ~5 to ~50 × 10^6 m^3, within a time of emplacement from 8 to 283 days. Different emplacement mechanisms as well as highly variable time averaged lava discharge rates (TADR; Harris et al., 1997) were encountered.

2. Input data and methods

2.1. Input dataset

The selected effusive activities occurred over a time interval of ~20 years: from October 1986 to December 2006. A series of DEMs has been collected to represent pre- (and/or post-) emplacement topographies for each effusive activity (Table 1). While photogrammetric-derived DEMs have been obtained by using the DEST algorithm (Favalli and Pareschi, 2004), LIDAR-derived DEMs have been processed and assessed as described in Favalli et al. (2009c).

For mapping purposes, DEMs were obtained in grid format with a 1 m cell size as described in Neri et al. (2008), while for the DOWNFLOW simulations, DEMs are obtained in grid format with a 10 m cell size. In addition to DEMs and DEM-derived images (described in the following sections), we used the LIDAR datasets to derive maps of the return pulses intensity (Mazzarini et al., 2007), and a 1 m resolution orthophoto, which helped in assessing whether flow units belong to older or newer events with respect to the time of image acquisition.

2.2. The mapping technique

The capability of mapping and analyzing lava flows, is being continuously improved by the application of new technologies, and more and more accurate and insightful results have been presented in recent years (e.g. Abrams et al., 1996; Stevens et al., 1997, 1999; MacKay et al., 1998; Rowland et al., 1999; Lu et al., 2004; Pyle and Elliott, 2006; Coltelli et al., 2007; Ventura and Vilardo, 2007; Zimbelman et al., 2008; Favalli et al., 2009c, 2010). Most of these advances have been possible thanks to the analysis of recently available remote sensing and geographic datasets, and to the use of geographic information systems (GIS).

In some cases, mapping recent lava flow fields can be quite easy. As an example, Favalli et al. (2006) presented a map of the 2002 lava flow field emplaced at Nyiragongo volcano (Democratic Republic of Congo) which was obtained by using only satellite imagery. In this case the new flow fields were easily distinguishable from the background. Unfortunately, an adequate image is not always available. In addition, standard satellite- or airborne-based sensors (working in the visible or near-infrared bandwidths) are not always suited to discriminate between a given flow field and the background due to very similar spectral responses, or owing to local lack of data, cloud coverage, or volcanic plumes.

Here, we approach the lava flow mapping at a considerably higher spatial resolution with respect to the above case. To derive enhanced boundaries of flow fields, we combine the analysis of the available conventional remote sensing imagery with the three approaches described below. Each approach has its own limitations (e.g. due to local lack of data or to local decrease in the accuracy), therefore, the final result is always improved by combining the contributions of all the approaches.

2.2.1. DEMs difference analysis

Mount Etna has been repeatedly surveyed to collect topographic and elevation data. Stevens et al. (1997, 1999), showed that the subtraction of the pre-emplacement topography from the post-emplacement one provides the volume of the lava flows (see also Wadge et al., 2006). If the obtained elevation difference map is accurate, it can effectively support flow field mapping. This concept has been recently applied and substantially refined by using very high resolution LIDAR-derived topographies, and so very detailed maps of the elevation difference between pre- and post-emplacement DEMs have been obtained (e.g. Favalli et al., 2009c; 2010; Fig. 1a).

2.2.2. Lidar intensity map

Mazzarini et al. (2007), showed that the intensity of LIDAR pulses reflected from the surface of lava flows, changes according to the different ages of the flows. Raw intensity data are normalized to account for the varying distance between the sensor and the reflecting surface during the airborne-based survey. Corrected data are converted into a grid, and an appropriate color table is applied to highlight the differences between different flow fields. Here we also used a linear combination between the LIDAR intensity map and the DEMs difference map to combine the two kinds of information in a single map (see Figs. 1b, 2, 3, 4).

2.2.3. Morphological analysis

Different types of images derived from high resolution DEMs of volcanic areas (e.g. shaded relief or slope maps) are currently used to enhance the mapping of local morphological and structural features (e.g. Mazzarini et al., 2005; Pyle and Elliott, 2006; Ventura and Vilardo, 2007; Csatho et al., 2008). The airborne LIDAR technology is nowadays available at an affordable cost and can provide accurate DEMs at a resolution of 0.5–1 m. Appropriate adjustments of raw input data can further reduce the error in elevation up to about 0.1 m (Favalli et al., 2009c). The analysis of these shaded relief and/or slope images can precisely reveal lava channels, levees and lava fronts; this evidence significantly help in delimiting single flow units and flow fields (Figs. 5, 6).

2.3. Lava flow simulations

2.3.1. DOWNFLOW code

To simulate the lava flow fields we used the probabilistic code DOWNFLOW (Favalli et al., 2005). This code treats lava flows as

Table 1
Summary of the sources used for the construction of the DEMs.

Year of the survey	Airborne technology	Elevation error (m)	Pre-emplacement topography for lava flow simulation	References
1986	Photogrammetry	2.69[a]	1986	Favalli et al., 1999; Neri et al., 2008
1998	Photogrammetry	1.98[a], 1.43[b]	1999 E, 1999 W, 2001 S, 2002 E	Tarquini et al., 2007; Neri et al., 2008; Favalli et al., 2009d;
2004	LIDAR	0.16[c]	2004	Mazzarini et al., 2005; Favalli et al., 2009c
2005	LIDAR	0.16[c]	2006 E, 2006 SW	Neri et al., 2008; Favalli et al., 2009c
2007	LIDAR	0.09[c]		Neri et al., 2008; Favalli et al., 2009c

[a] Calculated as elevation root mean square error (RMSE) in Neri et al. (2008).
[b] Calculated as RMSE in Favalli et al. (2009d).
[c] Calculated as explained in Favalli et al. (2009c).