High resolution Lidar data provide insights into the emplacement mechanism of gravity flows: a case study from the 1944 Somma-Vesuvius lava flow (Italy)

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**Abstract** A Digital Terrain Model derived from high resolution Lidar data allow us to determine the morphometric and physical parameters of a lava flow erupted from the Somma-Vesuvius volcano in 1944. The downstream variation of the morphometric parameters, which include slope, aspect, range, thickness, width, and cross sectional area, is analyzed, and the changes in viscosity, velocity and flow rate are estimated. The aim is to recognize different flow surfaces, to reconstruct the flow kinematics, and to obtain information on the mechanism of emplacement. Results indicate that the 1944 lava can be divided in three sectors: a near vent sector (NVS) characterized by a toe-like surface, an intermediate sector (IS) with an ‘a’ā-type, brittle surface, and a distal sector (DS) with a sheet-like, ductile surface. Lateral levees and channels are lacking in NVS, whereas they are well developed in IS. In DS, leveés grow up moving away from the vent. Fold-like surfaces occur in NVS and DS and reveal local shortening processes due to a decrease in the slope of the substratum and to overflows from the main channel. IS and DS emplaced between 18 and 21 March 1944, whereas NVS emplaced on 19 March and partly overlaps IS. The morphometric and physical parameters indicate that IS moved in a ‘tube’-like regime, whereas DS emplaced in a ‘mobile crust’ regime. The IS to DS transition is marked by an increase in velocity and flow rate, and by a decrease in thickness, width, cross sectional area, and viscosity. This transition is due to an abrupt increase in the slope of the substratum. The estimated velocity values are in good
agreement with the measurements carried out during the 1944 eruption. The analysis used here may be extended to other lava flows. Some gravity flows (debris/mud flows, floods, avalanches) have rheological properties and topography close to those of lavas, and the same effects can involve these flows. The approach used here may be useful for an evaluation of the hazard from gravity currents.

1. Introduction

Lidar (Light detection and ranging) technology from aerial platform is extensively applied for the mapping of the Earth surface because Lidar-derived data allow us to produce high resolution digital elevation models (DEMs) and digital terrain models (DTMs) (Dal Cin et al., 2005; Gamba and Houshmand, 2002; Glenn et al., 2006; Shrestha et al., 2005). The possibility to obtain information on the terrain topography and on the height and density of the vegetation cover makes this technique particularly suitable for studies on ecology, geomorphology, geology, hydrology, geotechnical engineering, as well as on natural hazard and natural resource monitoring (Irish and Lillycrop, 1999; Carter et al., 2001; Roering et al., 1999; Woolard and Colby, 2002; Hofton and Blair, 2002; Streutker and Glenn, 2006).

In volcanic environment, Lidar data acquired from aerial platform are commonly used to determine the volume of lava flows or pyroclastic flow deposits, and to measure topographic changes (Hofton et al., 2006; Mazzarini et al., 2005; Mouginis-Mark and Garbeil, 2005; Carabajal et al., 2005). Here, we use a different methodological approach: a Lidar-derived, high resolution (0.33 m x 0.33 m) DTM of a lava emitted from the Vesuvius volcano (Italy) in 1944 is analyzed with the aim to obtain geomorphological and morphometric information of the lava surface. This analysis allow us to (a) distinguish different types of flow surface and (b) clarify their kinematic significance, and (c) estimate some physical
properties of the lava flow. The results are discussed in light of the available volcanological data and information from laboratory models, and shed light on the mechanism of emplacement. The analytical approach used here may be extended to other natural gravity flows.

This paper is organized as follows. In a first section, we describe the geological setting of the Vesuvius volcano and provide a description of the 1944 eruption and of its effusive (lava flow) phase. In a second section, we illustrate the Lidar data characteristics and the DTM production along with the analytical methods used to extract the morphometric parameters and to estimate the physical properties of the lava flow. In the last two sections, we present and discuss the results and summarize the relevant conclusions.

2. Geological setting and chronology of the 1944 eruption

The Somma-Vesuvius volcano resulted from the superimposition of two edifices: the older Somma edifice, which is characterized by a summit caldera, and the younger, Vesuvius cone (1281 m a.s.l.), which is located within the caldera (Fig. 1; Santacroce, 1987). The Somma edifice is older than 18 ka and consists of lava flows and scoria deposits. The caldera resulted from the syn-eruptive collapses of four plinian eruptions occurred between 18 ka and AD 79. Sub-Plinian eruptions also occurred between 16.1 ka and AD 1631 (Andronico et al., 1996). Lava flows in alternation with explosive phases characterized the activity between AD 79 and AD 472, and mainly between AD 1637 and 1944 (Arnò et al., 1987). The lava flows of the 1637-1944 period cover the caldera floor and the southern and western flanks of the volcano (Fig. 1). The present-day Vesuvius crater formed during the AD 1944 eruption (Santacroce, 1987), which is the last eruption occurred at Somma-Vesuvius. At the present, the volcano is in a quiescent stage and only seismic and fumarolic activity occurs. The
volcanic hazard is, however, high because of 600,000 people live around the Vesuvius and an inverse relation between the duration of the quiescent periods and energy of the eruptions exists (Santacroce, 1987).

The 1944 eruption started on 18 March and stopped on 29 March. Four main phases characterized this eruption (Imbò, 1945, 1949): (1) lava flows (18 March, h 16.30 - 21 March, h 17.00), (2) lava fountains (21 March, h 17.00 - 22 March, h 12.00) (3) large explosions (22 March, h 12.00 - 23 March, h 14.00), (4) weak explosions (23 March, h 14.00 – 29 March). The effects of the eruption include the destruction of the villages of S. Sebastiano and Massa di Somma (Fig. 1) and of U.S. airforce planes stationed east of the Vesuvius crater. A few casualties caused by the explosion of a water tank run over by lava flows also occurred. The chronology of the first, effusive phase may be summarized as follows:

(1a) March 18, h 16.30 - Lava flows overflowed the northern and southern crater rims (Fig. 1). The northern lava moved initially on the northern, outer flank of the crater, and, bent to the west when it reached the caldera floor (Figs. 1 and 2). At h 22.30, the velocity of the northern lava flow within the Somma caldera floor was ~10 m/h. At h 23.00, a new outpouring of lava occurred from the western crater rim.

(1b) March 19 - The effusive activity become more intense and a new outpouring of lava occurred from the northern crater rim. This flow overlapped the northern lava emitted on 18 March.

(1c) March 21, h 1.00 - The northern lava flow reached the villages of S. Sebastiano and Massa di Somma, which are located about 5.3 km East of the Vesuvius crater (Fig. 1).

At the end of the eruption, the total length of this lava flow is 5.6 km. Taking into account that the northern lava flow emplaced in about 57 hours, the average flow velocity was 98 m/h. The present-day exposed lava has a length of 3.9 km because of the post-1944
buildings and quarries mask and/or dissect its distal sectors. The volume of the 1944 lava flows is \(~10^6\) m³ (Imbò, 1949) and the magma, which shows a phonotephritic composition (SiO₂=48.27 wt.%; Na₂O+K₂O=11 wt.%), has 38 vol.% of crystals and a temperature of about 1100°C (Marianelli et al., 1999; Morgan et al., 2004). Using these data and assuming H₂O=1 wt.%, we determine the apparent viscosity \(\eta\) and density \(\rho\) of the lava at the vent using the subroutines of Conflow (Mastin and Ghiorso, 2000). Results give \(\eta=10^4\) Pa s and \(\rho=3200\) kg/m³. These data allow us to estimate some physical properties of the 1944 lava flow (section 3.5).

3. Data and analytical methods

3.1. Lidar data and DTM

The Lidar data have been acquired on January 2005 from an aerial platform operated by Nuova Avioriprese SrL Company of Napoli (Italy) using an Optech ALTM 2050 Lidar System. The Lidar survey covered the northern and central sector of the Somma caldera, which includes the Vesuvius cone and the northern flow of the 1944 lava (Fig. 2a,b). The sensor, which acquires data at a rate of 50 kHz, was mounted on a fixed wing aircraft flying with a minimum airspeed of approximately 100kt. The data were collected from an altitude of approximately 700m, resulting in a footprint diameter of 20 cm for each laser pulse. Both first and last pulse data sets were acquired, each consisting of over 17 million individual postings covering an area of about 2,000 hectares. The data were collected in eight, 600m wide flightlines. The overlap of the flightlines is about 30%. The sensor utilizes a high-end Applanix Pos/AV Inertial Navigation System (INS), and a dual-frequency NovAtel
Millennium GPS receiver. The Vesuvius survey (Fig. 2a) has been georeferenced using a GPS reference station on an IGM95 geodetic point. The collected data were integrated with those obtained from GPS/INS, so obtaining the raw data. These were successively discriminated throughout the analysis of the times between first pulse and last pulse allowing us to discriminate between the elevation points and those related to vegetation and artificial features. The final cloud points covering the 1944 lava flow area, which is free of vegetation, resulted of about 4 million elevation points with density between 5 and 12 for square meter (Fig. 2a); the altimetry accuracy is $\leq 20$ cm. Using Surfer® 8 by Golden Software, a regular 0.33 by 0.33 m grid was created with the Lidar elevation points by means of the Kriging interpolation method (Oliver and Webster 1990). The resulting DTM of the 1944 lava flow is shown in Fig. 2b.

For the estimate of the lava flow thickness we used two 5 meters resolution DTMs of comparable accuracy derived from altimetry data collected before and after the 1944 lava flow emplacement. The DTM representing the topography before 1944 was produced by using elevation data derived from a contour map of the Italian Military Geographic Institute on 1900. This map has a 1:10,000 scale (contour interval 5 m). The DTM representing the topography after 1944 was produced by using the Regional Topographic Map (1:5,000 scale) by contour lines and altimetric points interpolation. The thickness of the 1944 lava was estimated as the difference between this latter DTM and that representing the pre-1944 topography.

### 3.2. Slope, range and aspect

We use the DTM produced by the Lidar height data of the 1944 lava flow to extract the following topographic parameters: slope, range and aspect. Slope is determined for each grid
node following Moore et al. (1993). The range is calculated from the difference between the maximum and minimum altitude within a 0.99x0.99 m (3x3 grid nodes) cell. The aspect, which measure the downhill (dip) direction of each node, is estimated following Wilson and Galland (2000). The maps of the slope, range and aspect, and the statistics of these three parameters are reported in Fig. 3.

3.3. Blocks and depressions

We generate a topographic map with contour lines spaced at 1 m height interval and identify, in a first step, all the contour lines representing closed polygons following Ventura and Vilardo (2006). In a second step, we select the closed polygons containing grid nodes with altitude higher than that of the enclosing contour line. These polygons represent local morphological heights, i.e. blocks of lava. We also select the polygons containing the grid nodes with altitude lower than that of the contour line. These polygons represent local depressions.

3.4 Geomorphology and variation of the topography with the distance from the vent

The data from Figs. 3 and 4 and the DTM from Lidar heights (Fig. 2b) allow us to draw a geomorphological map of the 1944 lava flow (Fig. 5). In this map, we recognize the following flow facies: flow levée, toe-like flow, sheet flow, folded surface, lobe-like surface, and ridge. The distribution of blocks and depression (Fig. 4a, b) is also included in the map together with the inferred flow directions, cracks, and breaks in slope. These latter represent pre-1944 artificial barriers overlain by the lava.
The variation of the topographic features of the lava flow at different distance from the vent is analyzed by measuring the thickness $h$ and slope $\alpha$ of the lava in 65, 50 m spaced locations along a longitudinal section (Fig. 2b) following the method described in the section 3.1. The width $w$ and cross sectional area $A$ of the lava are measured along 65 cross sections oriented perpendicular to the longitudinal section. The results of these measurement are summarized in Fig. 6.

3.5 Physical parameters

The collected data (Fig. 6) allow us to estimate some physical parameters of the 1944 lava flow and to analyze their downstream variations. These parameters are: the relative viscosity change, the change in the apparent viscosity, the flow rate, and the flow velocity. The relative viscosity change $\eta(x)/\eta(o)$ is given by (Baloga et al., 1998):

$$\eta(x)/\eta(o) = \frac{(h(x))^3 w(x) \sin(\alpha(x))}{(h(o))^3 w(o) \sin(\alpha(o))}$$

(1)

where $h$ is the thickness, $w$ is the flow width, and $\alpha$ is the slope angle. The subscripts $o$ and $x$ refer to an arbitrary reference location and to the distance from $o$, respectively. Assuming that the apparent viscosity at $o$ (Fig. 6a) is the magma viscosity $\eta=10^4$ Pa s (see section 2), the downstream change of the apparent viscosity is:

$$\eta_{\text{app}(x)} = \eta(\eta(x)/\eta(o))$$

(2)

Because of the high crystal content (38 vol.%; sections 2) of the 1944 lava, we assume a Bingham rheology and estimate the flow rate $Q$ by (Sakimoto and Gregg., 2001):

$$Q = \frac{C_1 h(x)^3 w(x) \tau}{(3 \eta_{\text{app}(x)})[1-C_2(\sigma/\tau)+C_3(\sigma/\tau)^2+C_4(\sigma/\tau)^3]}$$

(3)

where $C_1$ to $C_4$ are constant coefficients; the yield strength $\sigma$ and the shear stress $\tau$ are:
\[ \sigma = hg\rho w \]  
\[ \tau = h\rho g \sin \alpha \]  

where \( g \) is the gravity (9.8 m/s\(^2\)) and \( \rho \) is the density (3200 kg/m\(^3\); section 2). The flow velocity \( u \) is:

\[ u = Q/A \]  

where \( A \) is the cross sectional area of the flow (see Fig. 6). These parameters are determined by putting the values of \( t, w, \alpha, \) and \( A \) determined at different distance \( x \) from the reference point \( o \) in the equations 1-6. The variations of \( \eta(o)/\eta(o), \eta_{app(o)}, Q \) and \( u \) are summarized in Fig. 7.

4. Results

The geomorphological map of the 1944 lava (Fig. 5) shows that the flow can be divided in two main sectors: (1) a near vent sector (hereafter NVS) characterized by toe-like flows, and (2) an intermediate-distal sector (hereafter IDS), which is characterized by flows within a channel. NVS extends from the northern flank of the Vesuvius crater to the northern caldera wall for a distance of 500 m (Fig. 5). In NVS, the local flow directions range from NNW to NE-SW and folded surfaces affect the lower slopes of some toe-like flows, where the substratum is subhorizontal (Fig. 6). NVS also shows the highest values of \( h \) (27 m), \( w \) (250 m), \( A \) (7200 m\(^2\)), and \( \alpha \) (12°) of the whole 1944 lava flow (Fig. 6). IDS extends for a distance of 2800 m within the E-W striking natural valley delimited to the north by the caldera wall and to the south by the Vesuvius crater and Colle Umberto tholoid (Fig. 1). The local flow directions are generally between WSW and WNW, but some directions are towards the North
(Fig. 5). These latter directions occur on the northern boundary of the lava, where the flow shows a folded facies. In IDS, a sheet flow facies characterizes the lava at a distance >1700 from the vent (distal sector, hereafter DS), whereas cracks and ridges concentrate in sectors of the flow located between 500 and 1700 m from the vent (intermediate sector, hereafter IS) (Fig. 5). The distributions of the Lidar-derived topographic parameters (slope, range and aspect) highlight the differences in the topography of NVS, IS, and DS (Fig. 3). The NVS values of the mean, skewness and kurtosis are in between those of IS and DS. With respect to the IS parameters, those of DS show higher values of the arithmetic mean (Fig. 3). The kurtosis values of the IS distributions are higher than those of DS. With respect to the IS surface, the DS is characterized by a lower number of blocks and depressions (Figs. 4 and 5). The mean value of $h$ is 12 m in IS and 6 m in DS (Fig. 6b). In IS, the mean values of $w$ and $A$ are 78 m and 930 m$^2$, respectively, whereas they are 57 m and 205 m$^2$ in DS (Fig. 6d,e). This decrease in $h$, $w$ and $A$ from IS to DS is associated to an increase in the slope of the substratum (Fig. 6a,c). In IS, the mean slope is 2°, whereas it is 9° in DS. The mean values of $\eta_{\text{app}(x)}$, $Q$ and $u$ in IS are $\sim 10^4$ Pa s, 6535 m$^3$/h, and 12 m/h, respectively (Fig. 7). The DS flow is characterized by lower values of the apparent viscosity ($\eta_{\text{app}(x)}$ $\sim 10^3$ Pa s), and by higher values of the mean flow rate ($Q=21574$ m$^3$/h), and velocity ($u$=163 m/h).

5. Discussion

The results of the analysis of the Lidar data of the 1944 lava allow us to put constraints on the kinematic significance of the different flow facies and on the mechanism(s) of emplacement.
The NVS facies consists of toe-like flows that superimpose on the IS lava, which was emitted on 18 March 1944. Taking into account this observation and the chronology of the 1944 effusive phase, the NVS flows represent the outpouring of lava occurred on 19 March. Therefore, the NVS thickness (Fig. 6a, b) represents the sum of the thicknesses of the lava flows erupted on 18 and 19 March. This prevents a reasonable estimate of the thickness of the lavas emitted on 19 March and, as a consequence, of its velocity. The folds of the NVS toes, which are located where the lava mantles the base of the Vesuvius cone, can be interpreted as shortening structures. According to the results from experimental models on lava flows (Gregg et al., 1998; Bagdassarov and Pinkerton, 2004) and observations on other natural flows (e.g. at Karisimbi volcano; MacKay et al., 1998), the NVS folds formed due to a decrease in the velocity of the lava related to a decrease in the slope of the substratum (see Fig. 6a,c).

The IS lava shows a complex morphology characterized by a channel flow, lateral levées, blocks, depressions, rafts and cracks (Fig. 5). All these features are consistent with a ‘a‘ā-type lava (Kilburn and Guest, 1993) and testify the occurrence of brittle crust. The width of the southern IS lateral levée further increases downstream, whereas the northern levée is poorly developed or, in many places, lacking (Fig. 5). This indicates that the IS flow moved prevalently on the right (northern) side of the pre-existing valley. As a result, the southern levée represents a stagnant zone of the IS flow. In the proximal zone (section A-B in Fig. 8), a topographic profile across the IS lava shows a well-defined channel and lateral levées. Moving away from the vent, the levées are less defined (sections C-D and E-F in Fig. 8), and can be recognized only from a detailed analysis of the Lidar-derived topographic parameters of the flow surface (Figs. 3 and 5). The downstream widening of the IS southern levée, the flattening of the levées topography, and the occurrence of lobe-like surface in the more distal levée of the IS flow (Figs. 5) are features frequently observed in other basaltic and silicic lava
flows (Harris et al., 2004 and reference therein) and testify the downstream evolution from a more proximal, stable-transitional zone, to a more distal dispersed flow zone (Lipman and Banks, 1987). The stable/transitional zone is characterized by a poorly to medium developed crust, whereas the dispersed zone shows a well-developed crust that fully covers the molten interior of the lava. According to the above observations and data from Fig. 5, we conclude that most of the IS flow is covered by a crust.

The presence of a fold facies associated to local northward flow directions in some places of the northern boundary of the IS flow indicates shortening (Fig. 5). In some places, the fold facies superimpose on the northern IS levée. Therefore, the folded facies can be interpreted as overflows from the main, E-W striking channel. These overflows moved orthogonally to the strike of the channel and filled the morphological depressions located at the base of the Somma caldera wall (see Fig. 2).

The DS lava is mainly characterized by a sheet-like surface (Fig. 5). Levées are lacking in the more proximal portion of DS and gradually develop moving away from the vent. The number of blocks and depression slightly increases in the channel as the levées build up downflow (Figs. 4 and 5). The width of the DS lava also increases moving away from the vent (Fig. 6). The sheet-like facies and the low number of blocks and depressions indicate that the DS surface is less fragmented of that of the IS flow. In addition, the lack of cracks in DS suggests a prevailing ductile deformation of the surface (Kilburn, 2004). This imply that the DS crust is poorly developed and less extended of that of the IS lava. This conclusions is supported by the observation that the IS lava is wider of the DS flow (Fig. 6), being the crust coverage of a lava proportional to the flow width (Cashamn et al., 2005).

The DS surface is similar to the morphological structures of the ‘mobile crust’ regime obtained in experimental models on lava flow emplacement (Griffith et al., 2003; Cashamn et al., 2005), whereas the IS surface mirrors the morphologies of the ‘tube’ and ‘transitional’
flow regimes. The ‘mobile crust’ surface consists of free dispersed fragments and it is related to high effusion rates and velocities. The ‘tube’ and ‘transitional’ regimes, which are characterized by stationary and non-stationary surfaces, are promoted by lower effusion rates and velocities. With the aim of further constraint this interpretation of the IS and DS surfaces in terms of flow regimes, we estimate (a) the adimensional parameter $\psi = ut_s/h$, which is a measure of the solidification time $t_s$ relative to the advection time $h/u$ expected without solidification (Griffith et al., 2003 and reference therein), and (b) the Rayleigh number $Ra$:

$$Ra = g\beta(\Delta T)h^3/\kappa \nu$$

(7)

where $\beta$, $\kappa$, $\nu$, are the fluid’s thermal expansion coefficient, the thermal diffusivity, the kinematic viscosity ($\nu = \eta/\rho$), and $\Delta T$ is the difference between the initial temperature (that of the flow interior), and the solidification temperature (that of the cooled surface). These two parameters controls the transition from a ‘mobile crust’ regime to a ‘tube regime’ (Cashamn et al., 2005). For the determination of $\psi$ and $Ra$ in IS and DS, we use the appropriate values of $h$, $u$, and $\eta_{app(x)}$ (Figs 6 and 7), and set $\rho = 3200$ kg/m$^3$ (section 2), $\beta = 2 \times 10^{-5}$°C$^{-1}$, $\kappa = 4 \times 10^{-7}$ m$^2$/s, $\Delta T = 300$ K, and $t_s = 10$ s (Cashamnn et al., 2005). Results are reported in Fig. 9. Most of the DS points fall within the field of the ‘mobile crust’ flow regime, whereas the IS points are within the ‘tube’ field. According to these results and to the above reported qualitative observations, we conclude that the IS and DS facies are indicative of flows moving in ‘tube’ and ‘mobile crust’ regimes, respectively. Furthermore, $Q$ and $u$ of the DS flow are one order of magnitude higher than those of the IS lava (Fig. 7), a feature consistent with the observation that an increase in the effusion rate and velocity marks the ‘tube’ to ‘mobile crust’ transition (Griffith et al., 2003).

An increase in $\alpha$, a decrease in $h$, and an abrupt constriction of $w$ characterize the transition from the IS flow to DS (Fig. 6). These changes are associated to an increase in $u$ and a decrease in $\eta_{app(x)}$ (Fig. 7). This latter feature is relatively anomalous in lava flows
because the viscosity generally increases moving away from the vent due to cooling and crystallization (Pinkerton and Stevenson, 1992; Harris et al., 2005). We point out, however, that (1) the viscosity estimates of the 1944 lava refer to the flow as a whole, i.e. external solid crust and molten interior, (2) the IS flow, which shows a well-developed crust and moved in a ‘tube’-like regime, is expected to maintain a nearly constant temperature of the interior for long distances (Sakimoto and Zuber, 1998), (c) the DS flow moved in a ‘mobile crust’ regime, in which the crust represents only a dispersed fraction of the molten flow. Therefore, it is not surprising that, before the final cooling of the 1944 lava, the DS viscosity is lower than the IS viscosity (Fig. 7). Anyway, this decrease in viscosity is not exclusive of the 1944 lava. It has been also observed in other flows (e.g. at the Ascreaus Mons flow; Peitersen et al., 2001).

At Vesuvius, the reduction of the channel width and the increase in the slope of the substratum could be responsible for the IS to DS transition (Fig. 6). According to results from experimental models and observations of active lavas (Gregg and Fink, 2000; Cashamn et al., 2005), an increase in slope induces a narrowing of the flow, an increment of velocity, and the breaking of the surface crust. Our data are consistent with these features and show that, at the IS to DS transition, the slope of the substratum increases from 2° to 9°, the velocity increases and the flow width decreases. As a conclusion, the IS to DS transition is related to an abrupt change in the slope of the substratum on which the flow emplaced. Finally, we point out that (a) the mean flow velocity of the 1944 lava flow estimated from our data is 96 m/h, a value in excellent agreement with that deduced from the volcanological information (98 m/h; section 2), and (b) the average value of the IS velocity, which is 12 m/h, is consistent with that observed during the eruption (~10 m/h; Imbò, 1945).
6. Conclusions

The analysis of the high resolution Lidar-derived DTM of the 1944 lava flow of the Vesuvius volcano allow us to estimate some relevant topographic and physical flow parameters. The joint interpretation of these parameters and the recognized flow facies (NVS, IS and DS) shed light on the flow kinematics and on the mechanisms of emplacement. The relevant conclusions of our work can be summarized as follows. NVS flows were emitted on 19 March and superimposed the flows emitted in the previous day. The IS flow is characterized by a brittle crust and moved in a prevailing ‘tube’ regime, whereas the DS flow shows a sheet-like, ductile surface, and moved in a ‘mobile crust’ regime. These two regimes and the morphology of the flows are consistent with a decreases in the apparent viscosity from IS to DS. The IS to DS transition is due to an abrupt increase in the slope of the substratum and to a reduction of the flow width. These two factors are responsible for the increment in the velocity and effusion rate. The velocities of the 1944 lava are consistent with those estimated from volcanological data.

The approach used here for the analysis of the 1944 lava may be extended to other lava flows of the Earth and other planets, for which, in many cases, only topographic data are available. There are many other gravity currents, including debris/mud flows, floods, avalanches that may have rheological properties and topographic features like those of lavas. The same effects reported in this work could be recognized in these flows. The analytical method reported here could be useful for the evaluation of the hazard from gravity flows and for the planning of regions subjected to flow invasion.
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References


Figure captions

Fig. 1. Location and geological sketch map of the Somma-Vesuvius volcano (modified from Santacroce (1987)) superimposed on a shaded relief image of the Digital Terrain Model (DTM; UTM WGS84 projection, distance in meters). The lava flows of the 1944 eruption are in red. The location of the villages of Massa di Somma and S.Sebastiano are also reported.

Fig. 2. (a) Area covered by the Lidar survey (June 2005) and sampling density (number of data/m²) (UTM WGS84 projection, distance in meters). (b) DTM (1 m x 1m) of the area covered by the Lidar survey and DTM (0.33 m x 0.33 m) of the 1944 lava flow. The longitudinal section selected for the analysis of down-stream variations the altitude, thickness, slope, and width of the 1944 lava flow is also reported (Fig. 6).

Fig. 3. (a) Slope, (b) range, and (c) aspect maps of the 1944 lava flows obtained from the elaboration of the Lidar data of Fig. 2b. The statistics of these topographic parameters is also reported for different sectors of the flows (NVS, IDS, IS and DS, defined in section 4).

Fig. 4. (a) Location and number of blocks in the 1944 lava flow. (b) Location and number of morphological depressions in the 1944 lava flow.

Fig. 5. Geomorphological map of the 1944 lava flow obtained from the joint analysis of the DTM of the Lidar data and of the data reported in Figs. 3 and 4.
Fig. 6. Variation of the (a) altitude, (b) thickness, (c) slope, (d) width, and (e) cross sectional area of the 1944 lava flow with the distance form the vent. Data from 65, 50 m spaced locations along the longitudinal section reported in Fig. 2b. The location of the reference point $o$, which marks the transition from the NVS to the IS facies is reported in (a). The arithmetic mean of the thickness, slope, width and cross sectional area in the different flow facies (NVS, IS and DS) is also reported as straight line in (b),(c), (d) and (e).

Fig. 7. Variation of (a) relative viscosity change and apparent viscosity, (b) flow rate, and (c) velocity with the distance form the vent in the IS and DS facies of the 1944 lava. The arithmetic mean of the viscosity, flow rate and velocity in the IS and DS facies is also reported as straight.

Fig. 8. Topographic cross sections (A-B; C-D; E-F) in the IS facies of the 1944 lava flow from Lidar data.

Fig. 9. $Ra$ vs. $\Psi$ plot in IS and DS facies of the 1944 lava flows. The straight line dividing the ‘mobile crust’ regime from the ‘tube’ regime is from Cashman et al. (2005).