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Morphometry of scoria cones, and their relation to geodynamic setting: A DEM-based analysis

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ABSTRACT

The morphometry of a great number of scoria cones, belonging to volcanic fields of various geodynamic settings, has been measured and analyzed, addressing the question whether there is a relation between the prevalent cone shape in a given field and the geodynamic setting of the field itself. Morphometric analysis was carried out on freely downloadable digital elevation models (DEMs). The accuracy of the used DEMs and the associated error in scoria cone morphometry were determined by cross-comparing high-resolution LIDAR-derived DEMs, USGS NED, TINITALY DEM and ASTER GDEM. The 10-m TINITALY/01 and USGS NED DEMs are proven to be suitable for scoria cone morphometry, whereas ASTER GDEM can be used reliably for cones with volume greater than 30×10^6 m^3. According to a detailed morphometry of all scoria cones, we propose that the cones related to subductional setting show relatively higher values of H_{co}/W_{co} and lower values of W_{cr}/W_{co} than the cones related to extensional setting. The detected differences can be imputable to peculiar eruption dynamics resulting in slight but systematic changes in shape, and differences in lithological and sedimentological characteristics that govern post-eruptive erosion. To constrain the pathway of scoria cone erosion, the detected morphometric changes were also interpreted using a simple linear degradation model. Utilizing the obtained simulation results, the inferred initial cone base, and the age of scoria cones, we calculated a diffusion coefficient (K) for several dated cones, which are related to the prevalent climate. Our results, despite the high error associated, allow to assess the median K for all volcanic fields. Due to the complexity of the factors behind, it is not easy to understand if the prevalent shape characterizing a certain volcanic field is due mainly to sin-eruptive or post-eruptive mechanisms; however, our distinction between the two main geodynamic settings may be the first step to decipher these factors.

1. Introduction: scope and goals

Scoria cones are the most common, conical volcanic landforms, formed during strombolian, hawaiian, sub-plinian or phreatomagmatic eruptions of low-viscosity magma. They build up by the accumulation of proximal to distal graded welded and/or non-welded pyroclastic fragments of different size (e.g. McGetchin et al., 1974; Valentine et al., 2005; Mannen and Ito, 2007). The majority of scoria cones are monogenetic, i.e. the result of a single eruptive episode (Wood, 1980a; Walker, 2000) from a vent, or a few focal points along a fissure (Riedel et al., 2003).

For scoria cones, the term “monogenetic” is still largely used (e.g. Cebriá et al., 2011; Pérez-López et al., 2011); however, on the basis of the numerous works that document the complexity of scoria cone build-up (see, for example, Houghton and Schmincke (1989), for the Rothenberg scoria cone, East Eifel; Calvari and Pinkerton (2004), for the 2001 cone of Mt. Etna, Italy; and Pioli et al. (2008) and references therein, for the 1943–1952 eruption of Parícutin, Mexico), we restrict its usage to cones which formed in a relatively short time frame (hours to months), are small in volume and erupted predominantly mafic magmas, despite a long-lived eruptive stage.

Scoria cones are typically clustered in a separate cone field either on a flat surface (e.g. Michoacán–Guanajuato, Mexico, see Hasenaka and Carmichael, 1985), or as parasitic cones dotting the flanks of shield/strato volcanoes (e.g. Etna, see Corazzato and Tibaldi, 2006).

The morphology of scoria cones and their distribution in the field are the result of the interaction between regional tectonics and the eruptive behavior of the subsequent monogenetic eruptions, providing information about the past and current magma-feeding fracture system of the volcanic system (e.g. Takada, 1994; Tibaldi, 1995; Corazzato and Tibaldi, 2006). Also, they give insights into cone growth and degradation (e.g. Dohrenwend et al., 1986; Vesperman and Schmincke, 2000; Martin and Németh, 2006; Valentine et al., 2007).

Geomorphological studies on scoria cones have been promoted by accurate morphometric analyses (e.g. Porter, 1972; Wood, 1980a,b; Dóniz et al., 2008; Favalli et al., 2009a). Standard morphometric

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parameters of scoria cones, such as cone basal diameter (W_{co}), cone height (H_{co}), crater diameter (W_{cr}), as well as their aspect ratios (W_{cr}/W_{co} and H_{co}/W_{co}) have been lengthy described in previous key papers (Porter, 1972; Settle, 1979; Wood, 1980a; Hasenaka and Carmichael, 1985). Input data were measured on topographic maps and/or aerial photographs, and recently, scoria cone morphometry increased its efficiency and accuracy. Thanks to the progress in the remote acquisition of topographic information (e.g. Favalli et al., 2009a; Fornaciai et al., 2010; Inbar et al., 2011; Kervyn et al., 2011).

Although scoria cone morphometry benefitted from the improved DEM-based method and its application, some fundamental questions, such as how the geodynamic setting determines the overall cone shape, have rarely been addressed. Apart from the setting, the overall cone shape of a given volcanic field is influenced by erosion as well, since the field comprises different-aged cones subjected to smaller or bigger rate of erosion. Therefore, the aim of this work is to point out a possible relation between the prevalent cone shape in various volcanic fields and the geodynamic setting of the volcanic field itself, with respect to the role of erosion. To attain this complex purpose, an extensive morphometric analysis, using the best available DEMs, has been carried out for a large number of scoria cones belonging to several volcanic fields.

The steps we followed to match our main purpose have been:

i) downloading freely available DEMs;
ii) assessing the accuracy of these DEMs and the associated error in the morphometric analyses;
iii) taking into account for DEM accuracy and errors in order to select proper scoria cones (i. e. cone fields);
iv) measuring, analyzing and cross-comparing the morphometry, as results of the above three steps, of a great number of scoria cones belonging to volcanic fields of various geodynamic settings;
v) investigating the post-emplacement degradation path and its role in the final cone shape by comparing the current shape of dated cones with numerical simulation of cone degradation.

2. The topographic datasets

Nowadays, scoria cone morphometry can be extracted from two freely available digital elevation models (DEMs) that have an almost global coverage: the 90-m Shuttle Radar Topography Mission DEM (SRTM; http://www2.jpl.nasa.gov/srtm) and the 30-m Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global DEM (GDEM; http://www.gdem.aster.ersdac.or.jp). Kervyn et al. (2008) showed that the 90-m SRTM DEM (see Fig. 1) is not recommended for small-scale (500 m) and/or steep topographic features. Instead, medium- to high-resolution DEMs having a country-wide coverage are preferred, these being freely downloadable for several countries; examples are the 10-m USGS National Elevation Dataset (NED; http://seamless.usgs.gov) for the US, or the 10-m TINITALY DEM for Italy (Tarquini et al., 2012).

In the present work we used the following DEMs: a 2 m-resolution LIDAR-derived DEM; the 10-m resolution TINITALY DEM; the 10-m USGS NED; and the 30-m ASTER GDEM.

The LIDAR-derived DEM of Mt. Etna is a 2-m cell-size DEM acquired during the 2005 LIDAR survey (Favalli et al., 2009b). LIDAR data are often affected by systematic error. The data that we use in this work have been previously corrected for these errors, resulting in minimal root mean square (RMS) vertical and planimetric errors of ±0.16 m and ±0.48 m, respectively (Favalli et al., 2009b). The derived DEM covers an area of 616 km^2 comprising the largest part of Etna's flanks (Fig. 2).

The TINITALY/01 DEM dataset covers the whole Italian territory (Favalli and Pareschi, 2004; Tarquini et al., 2007). Input data for the area of interest (Mt. Etna) were taken from a 1:10,000 scale numeric

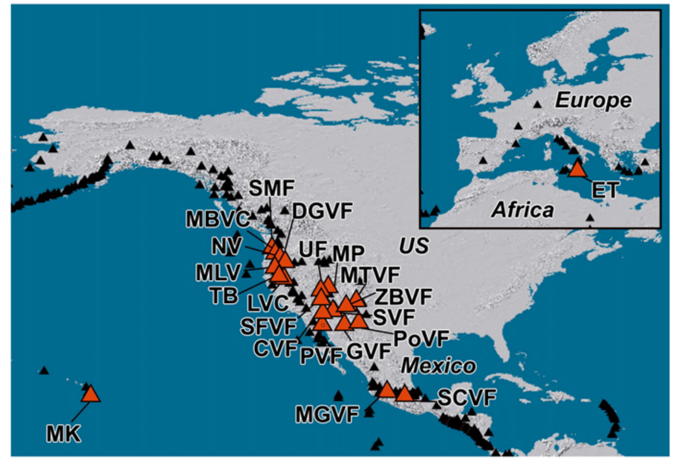

Fig. 1. The large red triangles indicate the location of the 21 selected cone fields. For acronyms, see Table 1. The small black triangles indicate volcanic centers. The DEM is the the 90-m Shuttle Radar Topography Mission (SRTM) DEM.

cartography published by the Provincia Regionale di Catania (Sicily) in 1999. The RMS vertical error of the DEM is 1.98 m (Neri et al., 2008). In this work we used the TINITALY/01 DEM in the form of a 10-m-resolution elevation grid.

The NED is a raster dataset that provides surface elevation information in a seamless form for the USA. The NED is a compilation of many data sources of varying horizontal datum, map projections, and elevation units assembled, converted to consistent units, and referenced to the NAD83 horizontal datum by the US Geological Survey (Gesch et al., 2002). The NED of the selected volcanic fields (some examples are in Fig. 2) was downloaded from the National Map Seamless Server provided by the USGS EROS Data Center (http://seamless.usgs.gov/) with a resolution of 10 m.

The ASTER GDEM, provided as 1-arc-second (~30 m) grid in geographic lat/long coordinates (ASTER, 2009), is released by METI (Ministry of Economy, Trade, and Industry of Japan) and NASA (United States National Aeronautics and Space Administration) and downloaded from http://www.gdem.aster.ersdac.or.jp. ASTER GDEM covers land surfaces between 83°N and 83°S with estimated accuracies of 20 m at 95% confidence for vertical data and 30 m at 95% confidence for horizontal data.

2.1. DEM accuracy

LIDAR, TINITALY and ASTER DEMs for Mt. Etna (see Fig. 3 and Table 1), and NED and ASTER DEMs for the San Francisco Volcanic Field (Fig. 4 and Table 1) were used to assess the discrepancy among DEMs of different sources and resolution. Vertical root mean squared (RMS) difference was calculated using the higher-resolution DEMs (LIDAR-DEM and/or NED) as reference, and measuring the vertical displacement (ΔZ) between the reference and the other DEMs in areas where no significant natural modifications occurred (i.e. where DEMs difference should be equal to zero and thus the residual ΔZ is an artifact). In the Mt. Etna area, since the high resolution LIDAR-DEM was used as master DEM, the RMS difference corresponds to the vertical root mean squared error (RMSE).

At Mt. Etna an area of 280 km^2 was selected for the RMSE calculation. The LIDAR DEM was used as master and TINITALY and ASTER DEMs as slave DEMs, obtaining RMSE of 2.3 and 9.1 m, respectively (Table 2). We found that a net vertical offset of 5.5 m exists between LIDAR and ASTER DEMs. Since an offset is irrelevant for the calculation of cone morphometric parameters, the RMSE of ASTER data was re-calculated after the correction of the offset, obtaining a