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Post-eruptive sediment transport and surface processes on unvegetated volcanic hillslopes – A case study of Black Tank scoria cone, Cima Volcanic Field, California

Gábor Kereszturi *, Károly Németh

Volcanic Risk Solutions, Institute of Agriculture and Environment, Massey University, Private Bag 11 222, Palmerston North, New Zealand

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ABSTRACT

Conical volcanic edifices that are made up from lapilli to block/bomb pyroclastic successions, such as scoria cones, are widespread in terrestrial and extraterrestrial settings. Eruptive processes responsible for establishing the final facies architecture of a scoria cone are not well linked to numerical simulations of their post-eruptive sediment transport. Using sedimentological, geomorphic and 2D fragment morphology data from a 15-ky-old scoria cone from the Cima Volcanic Field, California, this study provides field evidence of the various post-eruptive sediment transport and degradation processes of scoria cones located in arid to semi-arid environments. This study has revealed that pyroclast morphologies vary downslope due to syn-eruptive granular flows, along with post-eruptive modification by rolling, bouncing and sliding of individual particles down a slope, and overland flow processes. The variability of sediment transport rates on hillslopes are not directly controlled by local slope angle variability and the flank length but rather by grain size, and morphological characteristics of particles, such as shape irregularity of pyroclast fragments and block/lapilli ratio. Due to the abundance of hillslopes degrading in unvegetated regions, such as those found in the Southwestern USA, granulometric influences should be accounted for in the formulation of sediment transport laws for geomorphic modification of volcanic terrains over long geologic time.

1. Introduction

Hillslope processes occurring on soil-mantled flanks and flanks made from cohesionless particles are the focus of geologic and geomorphic studies to understand sediment transport mechanism and long-term landscape evolution (Arrowsmith et al., 1996; Heimsath et al., 1997; Roering et al., 2001; Tucker and Hancock, 2010). A local point on a hillslope is characterized by aggradation and erosion over its surface evolution (e.g., Carson and Kirkby, 1971), leading to either the increase or decrease of its elevation. In terms of numerical modeling of this temporal change of elevation at a local point, geomorphic transport laws were introduced, which are mathematical statements derived from a physical principle or mechanism (e.g., Dietrich et al., 2003). Each geomorphic transport law is characterized by a rate of sediment transport, or flux, which is defined as the mobilized sediment volume per unit width per unit time. This deterministic approach of describing sediment flux can be combined with local conservation of mass to express long-term elevation change at a location over time (Kirkby, 1971; Arrowsmith et al., 1996; Roering et al., 1999). In local and nonlinear models the sediment flux increases more rapidly when the critical slope angle is approached (Andrews and Bucknam, 1987; Roering et al., 1999). The nonlinear formulation of sediment flux can explain different types of hillslope processes, such as sediment/soil creep on gentle-slope and landslide on steep-slopes (e.g., Roering et al., 2001). Alternatives for local deterministic sediment flux formulation and landscape modeling, the non-local formulation of geomorphic transport laws have lately been proposed, using on the weighted topographic attributes in the upstream area (Foufoula-Georgiou et al., 2010) or based on sediment motion modeled as a random walk (Tucker and Bradley, 2010).

Diffusion-based modeling of volcanic terrains was introduced in volcanology by Hooper and Sheridan (1998). Diffusion-based modeling, which is mostly nonlinear slope-dependent model, was used to model transport-limited hillslope processes on scoria cones, or cinder cones (e.g., Hooper and Sheridan, 1998; Pelletier and Cline, 2007; Fornaciai et al., 2012; de' Michieli Vitturi and Arrowsmith, 2013). Scoria cones are defined here as any volcanic edifice with a conical geometry and an eruptive volume of generally ≤0.1 km^3; therefore, they are often called monogenetic (c.f. Németh and Kereszturi, 2015). They are built up from the near-vent accumulation of tephra from a wide range of eruption styles and numerous individual explosions of low silica, low

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* Corresponding author at: New Zealand Centre for Precision Agriculture, Institute of Agriculture and Environment, Massey University, Private Bag 11 222, Palmerston North, New Zealand.

E-mail address: g.kereszturi@yahoo.com (G. Kereszturi).

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viscosity magma (e.g., Di Traglia et al., 2009; Guilbaud et al., 2009; Németh et al., 2011; Dóniz-Páez, 2015). The typical eruptive spectrum of scoria cones includes lava-fountaining, Strombolian and violent Strombolian eruption styles (Riedel et al., 2003; Valentine et al., 2005; Kereszturi and Németh, 2012a; Courtland et al., 2013; Delcamp et al., 2014). The dominant grain size of ejecta on the edifice is lapilli (2–64 mm) and block/bomb (>64 mm) fractions with minor ash (<2 mm) contents (e.g., McGetchin et al., 1974; Wood, 1980). Despite their volumetrically small size, scoria cones are key volcanic landforms in monogenetic volcanic fields and their eruptions can have broader impacts, such as tephra accumulation (e.g., Ort et al., 2008), affecting short and long-term landscape evolution (Hooper and Sheridan, 1998; Pelletier and Cline, 2007), and estimating spatial distribution of vents in a volcanic field (Germa et al., 2013; Uslular et al., 2015). Numerical studies on scoria cone degradation aimed to develop predictive models to understand geomorphic changes of scoria cone flanks that might be used as a relative surface dating tool for volcanic fields (Hooper and Sheridan, 1998; Inbar and Risso, 2001; Kereszturi et al., 2013). Moreover, analyzing the geomorphology of scoria cones holds clues to understanding erosional and volcanic processes on remote and inaccessible terrains, such as the surface of Mars (Brož and Hauber, 2012; Brož et al., 2015), using remote sensing and topographic datasets.

Besides extensive literature on geomorphology, morphometry and numerical modeling, investigations on scoria cones have limitedly focused on understanding field-based sediment transport processes. Previous studies on scoria cones located in arid to semi-arid regions documented and identified the pre-dominant surface transport processes, such as debris flows, overland flows and rain splash (e.g., Dohrenwend et al., 1986; Wells et al., 1990; Hooper, 1999; Valentine et al., 2006). As a continuation of such field-oriented research, the present paper aims to reconstruct types and dominant sediment transport processes of scoria cones using a previously studied Black Tank cone in the Cima Volcanic Field in California (Fig. 1A). The Black Tank cone has completely exposed pyroclastic deposits with sparse-vegetation cover, providing an excellent insight into understanding the causes and consequences of eruption-related properties of scoria cones (e.g., grain size, grain shape, block and lapilli ratio) on the post-eruptive sediment transport and degradation processes on a 1000 year time scale. The assessment of hillslope processes operating on unvegetated volcanic hillslopes, such as on small-volume scoria cones, provides an improved conceptual model that can be used to formulate numerical models for predicting surface evolution of scoria cones.

2. Geological settings

The Cima Volcanic Field is located in the southern part of the Mojave Desert in California, southwestern United States (Fig. 1A). This field has hosted spatially and temporally distinct periods of intensive basaltic volcanism (Dohrenwend et al., 1984; Wells et al., 1985), in response to a regional-scale passive upwelling of asthenospheric mantle (e.g., Farmer et al., 1995). The monogenetic volcanism at the Cima Volcanic Field formed in three distinct phases between 7 Ma and present day based on K—Ar dating (e.g., Dohrenwend et al., 1984). Geochemically, the volcanic rocks are characterized by the dominance of hawaiite, alkali basalts and basanites, with distinct spatio-temporal patterns of composition and mantle xenoliths types (Wilshire et al., 1991; Farmer et al., 1995). The younger phases of volcanism (≤1.1 Ma) occupied a limited area of ≤150 km^2, and formed about 32 scoria cones. A few scoria cones had initial phreatomagmatic vent opening stages, forming circular tuff rings around the central vents (e.g., Dohrenwend et al., 1986). The scoria cones formed extensive lava flows, which were emplaced in a gently-sloping pre-eruptive terrain, up to 9 km in length, within an area of <10 km^2 (Wells et al., 1985). The lava flow morphotypes vary from pahoehoe to 'a'ā (e.g., Wells et al., 1985; Farr, 1992).

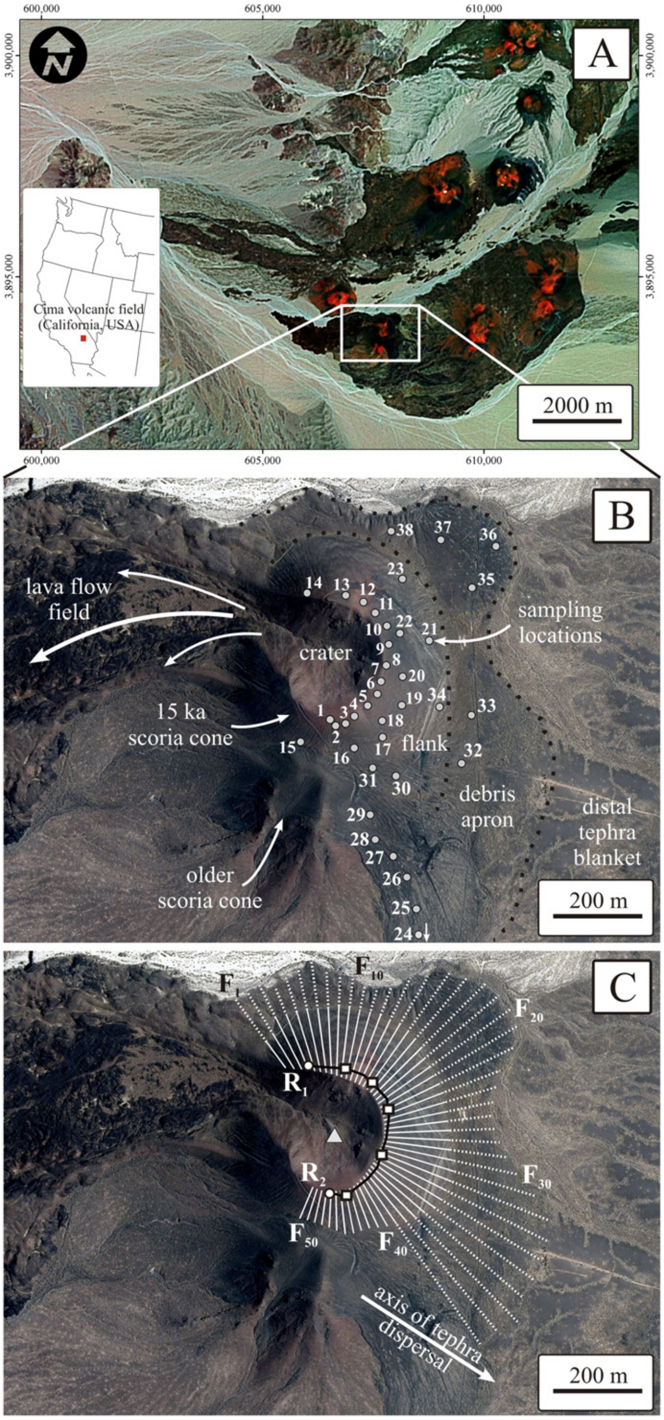

Fig. 1. (A) Location of the Cima Volcanic Field in California. (B) Orthophoto of the Black Tank cone with the major geomorphic features (dashed black line), such as crater, flank, debris apron and distal tephra blanket, as well as the numbered sampling locations. (C) Details of the analyzed profiles through the volcanic edifice. Lines with F_1–F_{51} are the radial profiles on the flank (white lines) and the apron (white dashed lines). R_1–R_2 is the profile along the crater rim. The white triangle is the mean center of the crater.

The youngest Black Tank scoria cone (N 35°10′53″ and W 115°49′1″) from the Cima Volcanic Field was selected (Fig. 1A,B) as the case study in the present investigation. This cone was previously called "Cone A" in Dohrenwend et al. (1986) and Black Tank cone in Wells et al. (1990). This cone has a well-constrained stratigraphic position and soil development stage (Dohrenwend et al., 1984; Wells et al., 1985). Furthermore, it has a quantitative age (ca. 15 ky) obtained using radiocarbon (14C) dating and cation-ratio dating of rock varnish (Dohrenwend et al., 1984, 1986; Dorn et al., 1986; Wells et al., 1990).