Earth and Planetary Science Letters 482 (2018) 52–61

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Using satellite imagery to identify and analyze tumuli on Earth and Mars

Serina Diniega[a,*], Simran Sangha[b,1], Brandon Browne[c,1]

[a] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., M/S 321-630, Pasadena, CA 91109, USA
[b] University of California, Los Angeles (UCLA), Los Angeles, CA, USA
[c] Humboldt State University, Arcata, CA, USA

ARTICLE INFO

Article history:
Received 28 May 2016
Received in revised form 10 October 2017
Accepted 13 October 2017
Available online xxxx
Editor: F. Moynier

Keywords:
tumulus
remote sensing
satellite images
Earth
Mars
inflated flows

ABSTRACT

Tumuli are small, dome-like features that form when magmatic pressures build within a subsurface lava pathway, causing the overlying crust to bulge upwards. As the appearance of these features has been linked to lava flow structure (e.g., underlying lava flow tubes) and conditions, there is interest in identifying such features in satellite images so they can be used to expand our understanding of lava flows within regions difficult to access (such as on other planets). Here, we define a methodology for identifying (and measuring) tumuli within satellite imagery, and validate it by comparing our results with fieldwork results of terrestrial tumuli reported in the literature and with independent measurements we made within Amboy Field, CA. In addition, we present aggregated results from the application of our methodology to satellite images of six terrestrial fields and seven martian fields (with >2100 tumuli identified, per planet). Comparisons of tumuli morphometrics on Earth and Mars yield similarities in size and overall shape, which were surprising given the many differences in the environmental and planetary conditions within which these features have formed. Given our measurements, we identify constraints for tumulus formation models and drivers that would yield similar shapes and sizes on two different planets. Furthermore, we test a published hypothesis regarding the number of tumuli that form per a square kilometer, and find it unlikely that a diagnostic "tumuli density" value exists.

1. Introduction

Tumuli are domed features found within inflated lava flows that reflect a localized uplift event (Fig. 1) (Anderson et al., 2012; Rossi and Gudmundsson, 1996; Walker, 1991). An inflated lava flow forms when a lava flow cools, but does not completely solidify and so retains a fluid interior insulated beneath a crust. Injections of lava from successive flows propagate through the interior and lift the crust, in addition to horizontally advancing the flow front (Keszthelyi et al., 2000). As the interior continues to cool, obstructions within lava flow pathways (e.g., tubes), or variations in lava flow rate due to eruption pulses or topographic confinement of the flow, can result in locally high magmatic pressures (Anderson et al., 2012; Calvari and Pinkerton, 1999; Hon et al., 1994). These pressures can cause the overlying crust to fracture into plates that tilt upwards, creating a domed landform with axial or radial fractures – a tumulus (Anderson et al., 2012; Rossi and Gudmundsson, 1996; Walker, 1991). As will be discussed, we found that tumuli are commonly small-scale features (∼10 m in width on both Earth and Mars); other inflated lava flow features that form through crustal uplift over a broader scale, such as lava rises (Walker, 1991) or sinuous tumuli (Orr et al., 2015), are more rectangular or irregular in planform shape and have flatter tops (S1).

As tumuli are hypothesized to form over lava pathways, they have been discussed within many terrestrial studies as potential proxy records of the subsurface lava flow structure (e.g., Anderson et al., 2012; Giacomini et al., 2009; Hon et al., 1994). However, within studies of tumuli, the definition of a tumulus was usually very descriptive and field-context specific, and relied upon some metrics that are not readily available from remote observations. To enable clear comparisons between flow fields and enhance the tumulus' usefulness as a proxy indicator of lava flow structure on Earth and other planets, a well-defined method to identify and measure tumuli within satellite images is needed. Towards that end, we have developed a method for the identification of tumuli within satellite images, using only planform dimensions and surface appearance, and apply it to satellite images of six terrestrial

---

[*] Corresponding author.
E-mail address: serina.diniega@jpl.nasa.gov (S. Diniega).
[1] Previously at Occidental College, Eagle Rock, CA, USA.

https://doi.org/10.1016/j.epsl.2017.10.028

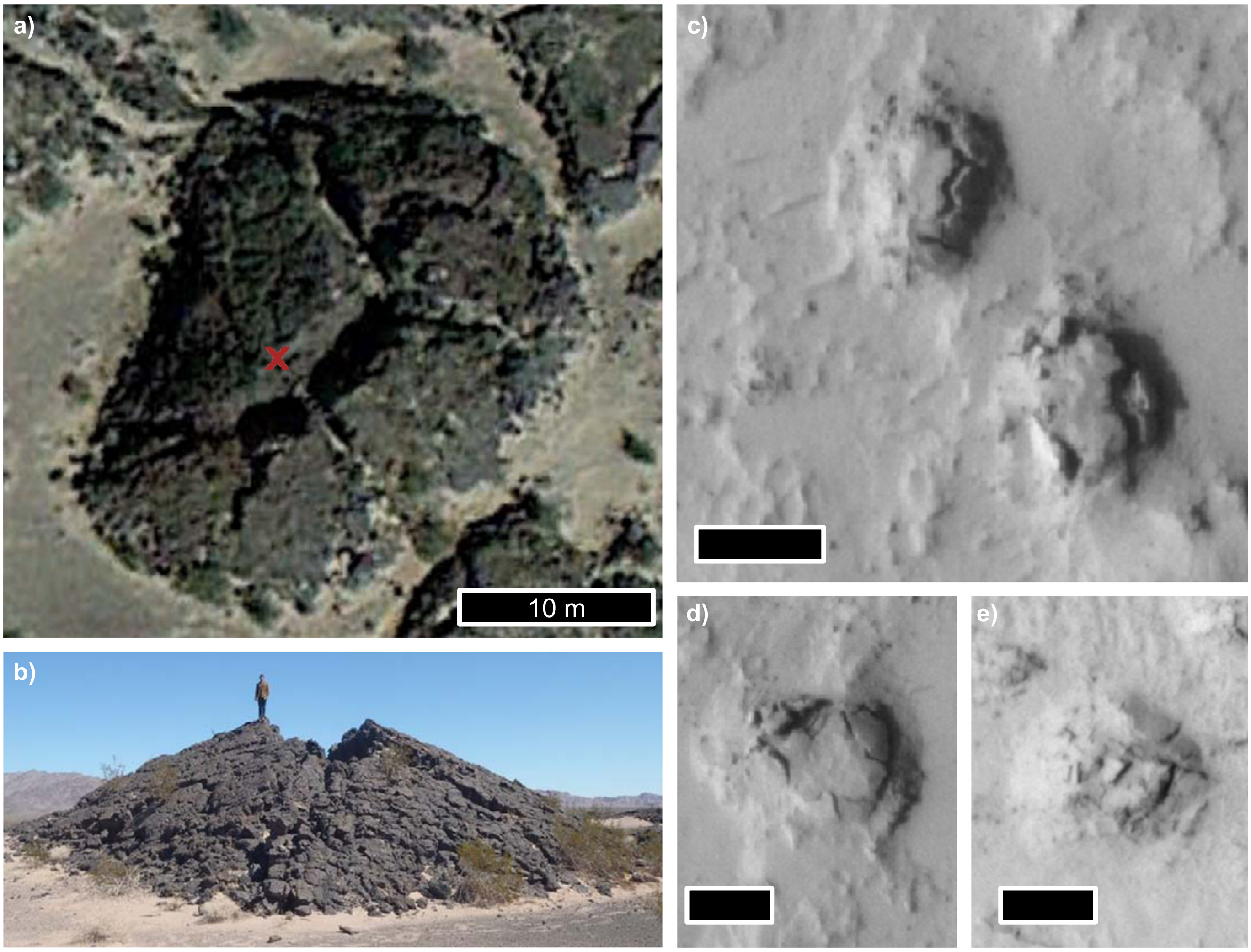

Fig. 1. Examples of the studied tumuli. (Left) Terrestrial tumulus example from the Amboy Crater Lava field/Earth Field site E6: (a) satellite and (b) ground view looking roughly west (SS, standing atop of the tumulus at the “x” in (a), is 1.83 meters tall; the axial crack in the center of (b) exits the tumulus on the lower left side in (a)). (Right) Martian tumuli examples: Satellite images of two regions within Elysium Planitia, Mars, showing (c/d) three tumuli from 3.2°S, 167.9°E, Mars Field site M4/HiRISE image PSP_002542_1765 with different clefting patterns, and (e) a tumulus from 5.6°N, 152.8°E, Mars Field site E6/PSP_006472_1855. In all images, the scale bar denotes 10 m. In all satellite images (here and in other figures), north is up. In (a), illumination is from the right and resolution is ∼1 m/pixel. In (c–e) (and all HiRISE images), illumination is from the left and resolution is 25 cm/pixel.

fields identified in the literature as containing tumuli (Section 2). We validate our method and results by showing consistency with published field study measurements from other terrestrial lava fields and with “groundtruth” field study measurements we collected over a portion of one of the remotely surveyed fields. We also use this methodology to remotely identify and measure possible tumuli within seven lava flows within Elysium Planitia, Mars (Section 3).

We discuss our terrestrial and martian results, and investigate implications after using our observation values within recent tumuli formation models (Section 4). We also discuss the implications of the similar mean tumuli dimensions and shapes between fields and planets, despite observed differences in the scale of other lava flow landforms (such as lava field or cinder cone size) and expected differences in planetary and lava flow conditions.

Additionally, we estimate the density of tumuli (number per square kilometer) within most fields, and use this to evaluate a hypothesis that tumuli fields have a characteristic tumuli per square kilometer density (Giacomini et al., 2009). Within two fields (one each for Earth and Mars), we also examine how tumulus sizes and number change within a field, depending on proximity to the flow’s terminus. While a full analysis of this type of relationship between tumuli characteristics and the tumuli population’s location within the flow is beyond the scope of this study, the results presented from these two lava flow fields supports the idea that such studies can connect these relict surface features to the larger-scale lava flow emplacement structure, thus enabling some interpretation of a flow’s emplacement history.

2. Methodology and observations

2.1. Identifying tumuli

Using detailed descriptions of the morphologies of different types of terrestrial lava flow features (Baloga et al., 2007; Duncan et al., 2004; Duraiswami et al., 2001; Hon et al., 1994; Rossi and Gudmundsson, 1996; Walker, 1991) along with hypotheses about the tumulus formation mechanism (Anderson et al., 2012; Rossi and Gudmundsson, 1996), a flowchart of specific planform morphological types (Supplemental Fig. 1/S1) was designed to differentiate between tumuli and other topographic features commonly found on inflated lava flows, such as lava rises. This flowchart focused only on planform morphology of the features, making it appropriate for use with satellite imagery. The primary intention