Earth and Planetary Science Letters 488 (2018) 46–58

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Lava delta deformation as a proxy for submarine slope instability

Federico Di Traglia [a,*], Teresa Nolesini [a], Lorenzo Solari [a], Andrea Ciampalini [b], William Frodella [a], Damiano Steri [a], Benedetto Allotta [c,d], Andrea Rindi [c,d], Lorenzo Marini [d], Niccolò Monni [d], Emanuele Galardi [d], Nicola Casagli [a]

[a] *Dipartimento di Scienze della Terra, Università degli Studi di Firenze, Via La Pira 4, 50121, Firenze, Italy*
[b] *Dipartimento di Scienze della Terra, Università di Pisa, Via Santa Maria 53, 56126, Pisa, Italy*
[c] *Dipartimento di Ingegneria Industriale, Università degli Studi di Firenze, Via Santa Marta 3, 50139, Firenze, Italy*
[d] *MDM Team S.r.l., official Spin-off company of the Università degli Studi di Firenze, Via Venezia 4, 50121, Firenze, Italy*

A R T I C L E I N F O

Article history:
Received 24 July 2017
Received in revised form 29 January 2018
Accepted 31 January 2018
Available online xxxx
Editor: T.A. Mather

Keywords:
lava delta
Stromboli volcano
submarine landslides
InSAR
volcano deformation
limit equilibrium analysis

A B S T R A C T

The instability of lava deltas is a recurrent phenomenon affecting volcanic islands, which can potentially cause secondary events such as littoral explosions (due to interactions between hot lava and seawater) and tsunamis. It has been shown that Interferometric Synthetic Aperture Radar (InSAR) is a powerful technique to forecast the collapse of newly emplaced lava deltas. This work goes further, demonstrating that the monitoring of lava deltas is a successful strategy by which to observe the long-term deformation of subaerial–submarine landslide systems on unstable volcanic flanks. In this paper, displacement measurements derived from Synthetic Aperture Radar (SAR) imagery were used to detect lava delta instability at Stromboli volcano (Italy). Recent flank eruptions (2002–2003, 2007 and 2014) affected the Sciara del Fuoco (SdF) depression, created a “stacked” lava delta, which overlies a pre-existing scar produced by a submarine–subaerial tsunamigenic landslide that occurred on 30 December 2002. Space-borne X-band COSMO-SkyMED (CSK) and C-band SENTINEL-1A (SNT) SAR data collected between February 2010 and October 2016 were processed using the SqueeSAR algorithm. The obtained ground displacement maps revealed the differential ground motion of the lava delta in both CSK and SNT datasets, identifying a stable area (characterized by less than 2 mm/y in both datasets) within the northern sector of the SdF and an unstable area (characterized by velocity fields on the order of 30 mm/y and 160 mm/y in the CSK and SNT datasets, respectively) in the central sector of the SdF. The slope stability of the offshore part of the SdF, as reconstructed based on a recently performed multibeam bathymetric survey, was evaluated using a 3D Limit Equilibrium Method (LEM). In all the simulations, Factor of Safety (F) values between 0.9 and 1.1 always characterized the submarine slope between the coastline and −250 m a.s.l. The critical surfaces for all the search volumes corresponded to the 30 December 2002 landslide, which involved the lava delta and its surrounding areas. InSAR data provided the post-effusive deformation field after the 2007 and 2014 flank eruptions, whereas LEM results highlighted that the accumulation of lava flows on the prone-to-failure SdF submarine slope is the main cause of the detected lava delta deformation. Lava delta instability, measured also at Pico Island (Azores) and Kilauea volcano (Hawaii), is evidence of the broader spectrum of instability phenomena that take place in the coastal or submarine area of the flanks of the volcanoes. At Kilauea, past lava deltas have moved faster than the surrounding slope and the recorded movements relate only to the collapses of the deltas themselves, producing rapid mass wasting near the coasts. In contrast, at Stromboli and Pico, lava deltas move at the same velocity as the surrounding slope. In these cases, the displacement at lava deltas can be considered as a proxy for the deformation of submarine slides. There are very few studies dealing with lava delta deformation, thus, the analysis presented in this work will benefit the monitoring of submarine slopes in other prone-to-failure coastal or island volcanic systems which have the potential to generate tsunamis.

1. Introduction

Lava deltas, formed by the accumulation of lava flows within the sea or a lake (Richards, 1959; Nemec, 1990; Lipman and

* Corresponding author.
E-mail address: federico.ditraglia@unifi.it (F. Di Traglia).

https://doi.org/10.1016/j.epsl.2018.01.038

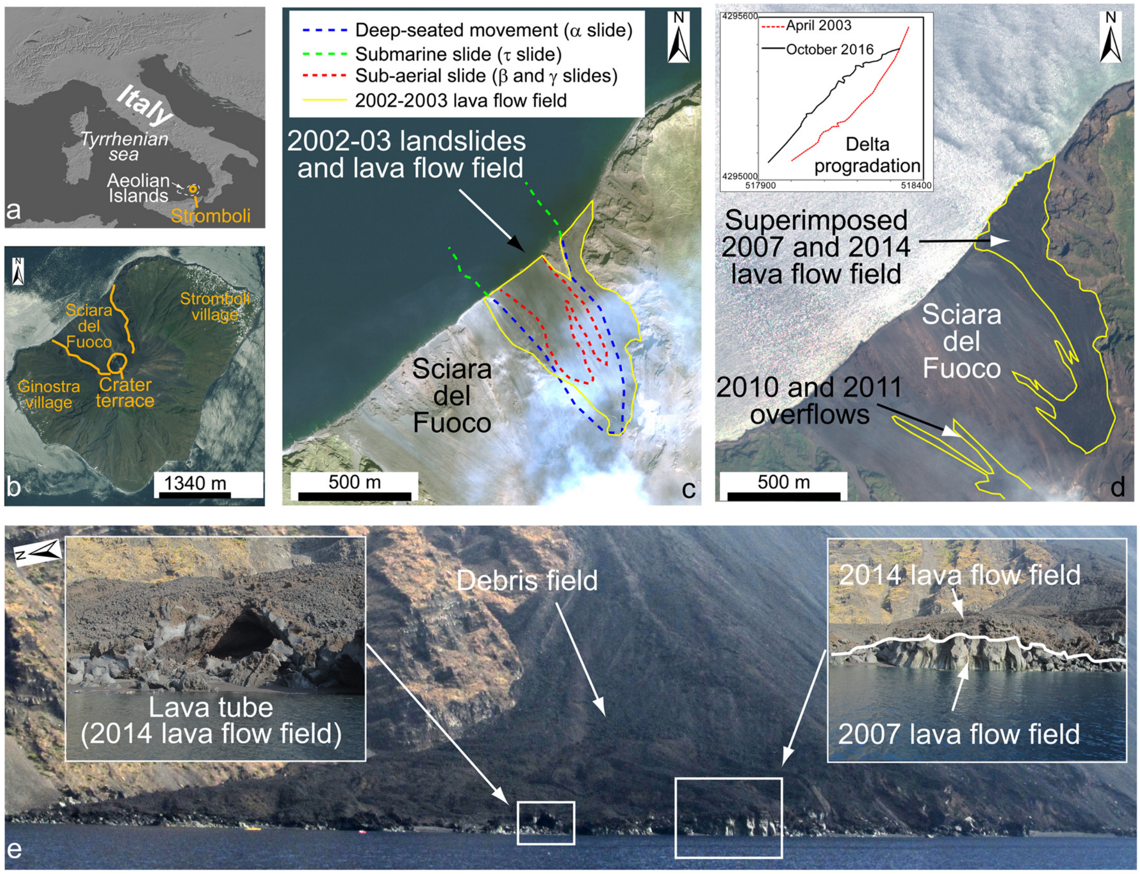

Fig. 1. a) Location of the Island of Stromboli within the central Mediterranean area; b) the Island of Stromboli. The main active geological features (Sciara del Fuoco and the crater terrace) and the two village areas are highlighted; c) IKONOS image collected on April 2003, emphasizing the 30 December 2002 landslide scarps, which are partially buried by the 2002–2003 lava flow field; d) PLEIADESNT image collected on May 2016, highlighting the superimposed 2007 and 2014 lava flow fields; the progradation of the lava delta, derived from the comparison between c) and d), is also shown; e) the present-day "stacked" lava delta (photo collected on October 2016 during the bathymetric survey), comprising the 2007 "low-elevation vent" lava flow (with a massive "aa lava flow" at the base) and the "high-elevation vent" lava flow, which consists of thin basal pahoehoe lava flows and extensive debris deposits produced by lava crumbling on the SdF extremely steep slope.

Moore, 1996; Ramalho et al., 2013; Bosman et al., 2014), are frequently unstable and delta collapses can potentially cause secondary hazardous events, such as littoral explosions and tsunamis (Jurado-Chichay et al., 1996; Mattox and Mangan, 1997; Chiocci et al., 2008a; Hildenbrand et al., 2012; Poland and Orr, 2014). Lava delta instability has been measured at Kilauea volcano (Hawaii), occurring since the emplacement and ending after complete collapse of the delta (Poland and Orr, 2014), and at Pico Island (Azores), associated with the creep of the southeastern flank of the island (Hildenbrand et al., 2012). Steep delta slopes are subject to frequent instability (failure) events, ranging from slow slope creep (i.e., slow, intergranular frictional sliding due to low strain rate) to fast moving debris flows (i.e., high strain rate), eventually evolving into turbidites (Nemec, 1990). This paper provides evidence that the study of long-term lava deltas deformation by means of the Interferometric Synthetic Aperture Radar (InSAR) data is fundamental to the monitoring of the stability of the submarine slopes in prone-to-failure coastal or island volcanic systems. Stromboli volcano was chosen as test-site, representing an optimal environmental setting and a case history of volcano slope instability phenomena where this methodology can be tested. The combination of displacement monitoring and slope stability modelling revealed that the observed deformation is related to the instability of the submarine slope. The proposed combination of field-based observations and advanced techniques, such as remote sensing and numerical modelling, provides information about both cause and extent of the detected lava delta deformation field, and it can be considered as a proxy for the deformation of submarine slides.

2. Case study: Stromboli

Stromboli is a volcanic island located in the Tyrrhenian Sea, off the southern coast of Italy (Fig. 1a). The entire volcanic edifice is ≈3 km high above the sea bottom and it is located at the NE tip of the Aeolian archipelago. It belongs to a late Quaternary, large volcanic complex of mostly basaltic to basaltic–andesitic composition (Tibaldi et al., 2009). The volcanic edifice has been affected by several episodes of sector collapse, the most relevant of which occurred ca. 13 ka in the NW part of the volcanic edifice, and which created the SdF depression (Tibaldi et al., 2009). Another large collapse event occurred at 5.6 ± 3.3 ka (Tibaldi et al., 2009), producing a massive landslide (0.73 ± 0.22 km^3, Di Roberto et al., 2010). The SdF depression is a landslide scar that extends down to 700 m below the sea level on the NW flank of the volcano and it is partially filled with volcaniclastic deposits and lavas (Kokelaar and Romagnoli, 1995; Rotonda et al., 2009; Nolesini et al., 2013) emitted from a summit crater terrace located at ≈750 m a.s.l. and from ephemeral vents located within the SdF (Fig. 1b; Marsella et al., 2012). Here, eruptive activity consists of typical persistent Strombolian activity, which is characterized by intermittent explosions from three vent zones (NE, SW and Central craters) located in the summit crater terrace (Calvari et al., 2014). This persistent Strombolian activity is often punctuated by periods dominated by stronger explosions and lava overflows from the crater terrace, and/or by lava flows from ephemeral vents (flank eruptions), as recently occurred in 2002–2003, 2007 and 2014 (Calvari et al., 2005; Marsella et al., 2012; Zakšek et al., 2015). During the 2002–2003