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Post-emplacment dynamics of andesitic lava flows at Volcán de Colima, Mexico, revealed by radar and optical remote sensing data

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Highlights:-We propose a novel approach for retrieving a 3D displacement field on lava
flows.

-We measure horizontal motion on a lava flow several months after its emplacement.

-Thermal contraction, loading and flow all contribute to the displacements.

Abstract : 281 words ; Main text : 9510 words, 4 tables, 11 figures, 65 references

Abstract:

We used optical and radar remote sensing datasets to map, estimate the volume, and measure the surface displacements of lava flows emplaced on the flanks of Volcán de Colima, Mexico by extrusion of lava dome material from the end of 2014 to early 2016. Our main result is that the flow motion of the lava contributes significantly to the recorded displacements several months after its emplacement. First, we mapped the deposits and estimated their volumes using two Digital Elevation Models (DEM), one derived from radar data acquired before the peak of activity and one derived from optical images acquired just after this peak of activity. Coherence information derived from the radar dataset added some temporal constraints on the timing of emplacement of various deposits. We thus estimated a mean extrusion rate of $1\text{--}2\text{ m}^3\text{ s}^{-1}$ between November 2014 and February 2015. We then used a new approach to reconstruct the 3D displacement field, taking advantage of images acquired by the same satellite, on both ascending and descending tracks, and using a physical *a priori* on the direction of horizontal displacements. Our results show that about 2 cm yr^{-1} of horizontal motion is still recorded a few months after the emplacement on the SW lava flow, which is the only one covered by the two-acquisition geometries. In order to differentiate the potential causes of the observed displacements, we modeled the thermal contraction of the lava flow using a finite element numerical method. Removing the contribution of thermoelastic contraction from the measured displacements enable to infer both the viscoelastic loading and flow motion effects from the residuals. Results show that, thermal contraction, flow motion and viscoelastic loading contribute significantly to the displacements recorded.

Keywords:

- Remote sensing, InSAR, 3D displacement field, lava flow, subsidence, thermal contraction.

1. Introduction:

Spaceborne remote sensing datasets, providing information with a good spatial coverage over areas that are difficult to access, have proven to be powerful tools to study lava flows. Radar images have the advantage that they are insensitive to cloud cover and solar lighting. They can be used to detect and map new lava flows with either coherence or amplitude based methods (Schaber et al., 1980; Zebker et al., 1987, 1996; Gaddis, 1992; Rowland et al., 2003; Dietterich et al., 2012). They are also commonly used to estimate their thickness and volume, and thus determine volcano extrusion rates (Stevens et al., 1999; Rowland et al., 2003; Terunuma, et al., 2005; Poland, 2014; Bato et al., 2016; Arnold et al., 2017), which is key information in terms of hazard assessment. Interferometry has been used to study the post-emplacement dynamics of lava flows (e.g. Briole et al., 1997; Lu et al., 2005; Ebmeier et al., 2012; Bato et al., 2016; Chaussard, 2016, see table 1), and in turn, calculate their material properties (Wittmann et al., 2017). However, most of these studies were performed on basaltic lava flows emplaced on gentle topographic slopes (see table 1), where lava flows are frequent and InSAR is highly effective. On the contrary, it is well-established that InSAR methods are more difficult to use on andesitic stratovolcanoes because of their steep topography and generally dense vegetation coverage, causing low coherence and noisy data (Pinel et al., 2011). A limitation to the use of InSAR to characterize post-emplacement deformation of lava flows is that, in the absence of additional measurements of the surface displacement such as GNSS or SAR acquired from a different satellite (Peltier et al., 2017),

radar images acquired by a given satellite for both the ascending and descending tracks are difficult to use to reconstruct the 3D displacement fields due to the lower accuracy in the north-south (N-S) direction (InSAR measurements being only sensitive to the displacements along the satellite line of sight, which horizontal projection is usually close to the east-west direction for both ascending and descending tracks). Thus, most studies consider that the Line of Sight (LOS) displacements measured result from vertical displacements alone. This assumption prevents the extraction of information about the lava flows horizontal displacement fields being extracted, and could introduce an error into the estimated vertical displacements.

Volcán de Colima, one of the most active volcanoes in North America, is located at the SW front of the Trans Mexican Volcanic Belt (Fig. 1), created by the subduction of the Cocos and Rivera plates under the North American plate. Volcanic activity is characterized by cycles of around one hundred years which culminate in a large Plinian eruption; the last major explosive eruption was in 1913 (Robin et al., 1987; Luhr and Carmichael, 1990).

A new episode of mostly effusive activity began in 1961, when the lava that had slowly infilled the crater left by the 1913 explosions reached the lowest notch in the northern crater rim, generating block-lava flows. Similar episodes of activity followed in 1975-1976 and 1981-1982. In 1991 the lava extrusion began to form a lava dome that fed new block-lava flows (Luhr, 2002). Collapses of the crater rim and the overflowing dome have since caused numerous block and ash flows, particularly in 2004-2005. Dome-building activity resumed in 2007. Vulcanian explosions destroyed the dome in early 2013, and a new dome began growing again overflowing from the crater and producing further lava flows in March 2013 (Capra et al, 2016).

At the end of 2014, an increase in eruptive activity was recorded, notably marked by the July 10 and 11, 2015 pyroclastic density currents (PDCs) which represented the largest runout since 1913 (Capra et al., 2016; Reyes-Dávila et al., 2016; Macorps et al., 2017). The 2015 eruption was not preceded by any detectable precursors in terms of edifice inflation or seismic velocity variations (Lesage et al., 2018). Before and after these events, large lava flows were emplaced on the volcano flanks (Reyes-Dávila et al., 2016). Activity reports describe active lava flows on the western (W) and south-western (SW) flanks from September–November 2014 to mid–February 2015, when no downward motion was observed (Sennert, 2015a). In July, 2015, just after the PDC occurrences, another lava flow formed on the southern (S) flank in the same channel as the PDCs (Sennert, 2015b). Most of studies about this high activity period deal with PDC deposits (Capra et al., 2016; Reyes-Dávila et al., 2016; Macorps et al., 2017) but lava flows should also be considered in order to properly characterize and understand the volcano activity.

The present study combines both radar and optical remote sensing data with the aim of determining where lava flows were emplaced as well as their volumes and their post-emplacment dynamics, in order to have greater insight into the 2014-2015 eruptive crisis of Volcán de Colima. New approaches are proposed to: (1) improve the remote sensing detection of lava flows on andesitic stratovolcanoes, and (2) reconstruct approximate 3D ground displacements associated with the emplacement of lava flows using InSAR LOS measurements on both the ascending and descending tracks from a single satellite, without any other additional observation. Finally, the thermal compaction of the lava flow is numerically modeled and its relative contribution together with the loading and downward flow effect, are investigated. An estimation of the magma bulk viscosity is also derived based on the downward lava displacement.

Figure 1: Map with footprints of optical and radar images used in this study. The red dashed line marks the edge of the Trans Mexican Volcanic Belt (TMVB) (red area in the inset). The large blue triangle shows the location of Volcán de Colima (CV). Green and blue rectangles are, respectively, footprints of Sentinel-1A ascending (Orbit A49, sub-swath 3) and descending tracks (Orbit D12, sub-swath 1) (for simplicity, only the bursts and sub-swaths used are delimited). The yellow rectangle delimits the extent of Tandem-X DEM. Inset shows the described area location (dashed blue rectangle) at a larger scale. The PLEIADES DEM coverage (10×13 km² centered on the edifice summit) is not displayed here for clarity.

Volcano (deposit year)	Time span (yrs)	Lava composition	Local slope	Ref
Africa				
Fogo (1995)	3	Basaltic	~3°	(Amelung and Day, 2002)
Piton de la Fournaise (1998–2007)	2–16	Basaltic	~17°	(Chen et al., 2018)
(2010)	0.3–3	Basaltic	~7°	(Bato et al., 2016)
Mt Nyamuragira (2004–2010)	0–5.5	Basaltic	~4°	(Samsonov and d’Oreye, 2012)
North America				
Paricutin (1943–1952)	55–68	Basaltic-Andesitic	~5°	(Chaussard, 2016)
(1943–1952)	56–65	Basaltic-Andesitic	~8°	(Fournier et al., 2010)
Santiaguito (2004–2005)	4–6	Dacitic	~21°	(Ebmeier et al., 2012)
Okmok (1958 & 1997)	0.5–3.5	Basaltic	~1°	(Lu et al., 2005)
Colima (1998)	4–8	Andesitic	~25°	(Pinel et al., 2011)
(2014–2015)	0.5–1.1	Andesitic	~18°	This study
Pacaya (2010)	0.1–4	Basaltic	~10°	(Schaefer et al., 2016)
Europe				
Etna (1986–1987 & 1989)	3–7	Basaltic	~23°	(Briole et al., 1997)
(1991–1993)	2–6	Basaltic	~13°	(Stevens et al., 2001)
Krafla (1975–1984)	8–20	Basaltic	~1°	(Sigmundsson et al., 1997)
Hekla (1991 & 2000)	2–25	Basaltic-Andesitic	~8°	(Wittmann et al., 2017)
South America				
Reventador (2002–2005)	3–6	Andesitic	~18°	(Fournier et al., 2010)
Lonquimay (1988–1989)	17–18	Andesitic	~4°	(Fournier et al., 2010)

Table 1: List of the InSAR studies related to lava flow post-emplacement deformations. Local slope was estimated from the SRTM DEM. Time span corresponds to the time lapse between the lava flow emplacement and SAR image acquisition.

2. Data and methods

2.1. Data and processing

Topographic changes induced by lava flow emplacement were estimated based on two Digital Elevation Models (DEM). The pre-eruptive DEM used is the TanDEM-X, 12 m resolution, provided by the German Space Agency (©DLR 2015) and obtained from X-band radar images acquired between January 2011 and August 2014 (see footprint on Fig. 1). A post-eruptive DEM was obtained using one stereo pair of Pleiades optical images (©CNES_2016, distribution AIRBUS DS, France, all rights reserved) acquired on 10 January 2016 and made available through an ISIS (Incitation à l'utilisation Scientifique des Images Spot, French initiative to promote the scientific use of Spot images) project. Pleiades panchromatic images have a nominal resolution of 0.5m. Along-track incidence angles of the two images are -9.3° and -13.1° , while the across-track angle varies between -14.5° and -9.6° . The DEM was computed using the NASA open source software Ames Stereo Pipeline (Broxton and Edwards, 2008). Disparities between the two images are searched for; this provides a point cloud of the surface topography which is then converted onto a grid regularly spaced every 3 m. In this way we obtain a Digital Surface Model, but as no vegetation is present on the region of interest, where lava flows are emplaced, it corresponds to a DEM.

Surface displacements induced by the lava flows were quantified based on 36 SAR images acquired from November 23, 2014 to February 10, 2016, on both ascending and descending tracks, by the European satellite Sentinel-1A with a Vertical-Vertical polarization (Table 2). Images were acquired in Terrain Observation by Progressive Scans SAR (TOPSAR) Interferometric Wide Swath mode (Zan and Guarnieri, 2006) and provided as Single Look Complex (SLC) images with a spatial resolution of 15.6 m in azimuth and 2.3 m in slant range (see Fig. 2 for spatio-temporal distribution of the dataset). As Volcán de Colima's flanks are steep, local topographic slopes are

close to or even greater than the incidence angle, inducing low resolution and a possible layover effect on the flanks facing the satellite. This is particularly true for the descending track where the incidence angle is very close to the volcano slope on the eastern flanks around the summit area ($\sim 35^\circ$). Ground area affected by low resolution was estimated and consequently masked based on acquisition geometries.

Interferograms as well as coherence images were computed on ascending and descending tracks from SLC images using the NSBAS processing chain as described in Doin et al (2012) and modified to allow for TOPSAR data ingestion (Grandin, 2015). Topographic phase contribution was removed using the SRTM Digital Elevation Model at 30 m resolution oversampled to 15 m. Interferograms were corrected for tropospheric phase delays using atmospheric data provided by the European Center for Medium Range Weather Forecast (ECMRWF) (Doin et al., 2009). Interferograms were then unwrapped using the ROI_PAC branch-cut unwrapping algorithm. Phase delays were converted to LOS ground displacements considering ground displacement as null in a 255x255 m reference area located at the basal part of the SW volcano sector (see Fig. 6–7). Cumulative LOS ground displacements for each successive date after to the first one were obtained by time series inversion, pixel by pixel, using a least squares method (Doin et al., 2012). Lastly, cumulative displacements were geocoded in UTM coordinates on the oversampled SRTM DEM used to correct the topographic phase delay (15x15 m). The time series analysis was performed on a restricted subset of the data to ensure good coherence over the lava flows. As the coherence was too low on lava flows for images acquired before the July eruption (Lesage et al., 2018), we only considered interferograms obtained from images acquired after August 2015 (see Fig. 2B–C).

Date	Orbite-Slice Sub-swath	Date	Orbite-Slice Sub-swath
23 Nov 2014	D12-4 IW1	24 Jul 2015	A49-1 IW3
08 Dec 2014	A49-1 IW3	02 Aug 2015	D12-4 IW1
17 Dec 2014	D12-4 IW1	17 Aug 2015	A49-1 IW3
01 Jan 2015	A49-1 IW3	26 Aug 2015	D12-4 IW1
10 Jan 2015	D12-4 IW1	19 Sep 2015	D12-4 IW1
03 Feb 2015	D12-4 IW1	13 Oct 2015	D12-4 IW1
18 Feb 2015	A49-1 IW3	28 Oct 2015	A49-1 IW3
02 Mar 2015	A49-1 IW3	06 Nov 2015	D12-4 IW1
11 Mar 2015	D12-4 IW1	30 Nov 2015	D12-4 IW1
23 Mar 2015	A49-1 IW3	15 Dec 2015	A49-2 IW3
04 Apr 2015	D12-4 IW1	24 Dec 2015	D12-4 IW1
28 Apr 2015	D12-4 IW1	27 Dec 2015	A49-2 IW3
22 May 2015	D12-4 IW1	08 Jan 2016	A49-2 IW3
06 Jun 2015	A49-1 IW3	17 Jan 2016	D12-4 IW1
15 Jun 2015	D12-4 IW1	01 Feb 2016	A49-2 IW3
30 Jun 2015	A49-1 IW3	10 Feb 2016	D12-4 IW1
07 Jul 2015	D12-4 IW1	25 Feb 2016	A49-2 IW3

Table 2: List of the Sentinel-1A SAR images used in this study. Information on the acquisition geometry for each track is provided in Table 3.