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Subsidence in the Parícutin lava field: Causes and implications for interpretation of deformation fields at volcanoes

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ABSTRACT

Assessment of volcanic hazards includes interpretation of ground deformation signal, which, at polygenetic volcanoes often results from the superposition of deformation due to pressure changes in the magmatic system and due to surficial processes such as cooling of emplaced lava. The deformation signal associated with emplaced lava is sometimes considered negligible if fields are decades old, but if the lava thickness is great, deformation may still be occurring, possibly leading to misinterpretation of the observed deformation. Here I evaluate the 2007–2011 ground motion of the 1943–1952 lava field of the Parícutin monogenetic cinder cone, Mexico. Interferometric Synthetic Aperture Radar (InSAR) time series reveal patchy subsidence restricted to the lava field and following linear rates up to 5.5 cm/year. There is a clear correlation between subsidence rates and topography suggesting a causal relationship with deposits or lava thickness. I estimate these thicknesses in the subsiding areas using pre- and post-eruption topographic maps and show that they reach up to 200 m. A numerical model for lava flow cooling was developed considering radiation and convection from the surface, conductive transfer inside the flow and to the ground, and vesiculation and latent heat generation at the top and bottom of the flow. The model shows that compaction induced by cooling of the thick deposits emplaced ~60 years ago explains the observed subsidence when conductive transfer to the ground is considered. These results demonstrate that thick deposits can keep deforming significantly even decades after their emplacement, emphasizing the importance of considering cooling processes when interpreting deformation fields at polygenetic volcanoes producing massive lava fields.

1. Introduction

Parícutin is a monogenetic cinder cone born in a cornfield in west-central México in 1943 (Pioli et al., 2008). Its eruption lasted until 1952 but the volcano's growth mainly occurred during the first year, in the explosive pyroclastic phase. During the following eight years it had quiet eruptions involving massive basaltic-andesitic lava flows that buried the nearby villages of Parícutin and San Juan Parangaricutiro (Wilcox, 1954; Fries, 1953; Hasenaka and Carmichael, 1987). The magma involved in Parícutin's eruption originated from the mantle and resided at shallow depths in a temporary system of dikes and sills, the dynamics of which were controlled by ascent in the primary conduit system: diminished rates of magma supply from depth led to withdrawal of the magma trapped in the shallow system (Erlund et al., 2010).

Cinder cones do not develop long-lived magma reservoirs, in opposition to polygenetic volcanoes, because they are active for only short periods of time (Luhr and Carmichael, 1985; Hasenaka and Carmichael, 1985; Cervantes and Wallace, 2003). When the eruption of a monogenetic volcano ends, the magma remaining in the conduit solidifies, increasing the strength of the crust and leading to melts selecting different pathways for the next eruption (De la Cruz-Reyna and Yokoyama, 2011). Thus, Parícutin possesses an extensive lava field and no magma reservoir, settings that are ideal to study deformation of lava flows and ash deposits emplaced decades ago. Subsidence in Parícutin's vicinity has been briefly noted by Fournier et al. (2010) and Chaussard et al. (2014), but no detailed analysis has yet been performed.

Here I use Interferometric Synthetic Aperture Radar (InSAR) to quantify the deformation associated with Parícutin's deposits emplaced over 60 years ago. InSAR has been successfully used to detect and monitor a variety of geohazards, from earthquakes, to land subsidence, and volcanic eruptions (e.g. Massonnet et al., 1993; Tralli et al., 2005; Amelung et al., 1999; Chaussard et al., 2013a, 2014; Lu et al., 2007; Chaussard et al., 2013b). However, InSAR works applied to volcanology tend to focus on magmatic processes and the deformation due to surficial processes such as lava cooling tends to be overlooked. For example, most InSAR works considering deformation at Kilauea, at the Galapagos volcanoes, or at Etna, which erupt frequently and produce significant lava flows, focus on magmatic processes (e.g. Baker and Amelung,

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2012, 2015; Lundgren et al., 2013; Plattner et al., 2013; Chadwick et al., 2006; Yun et al., 2006; Hooper et al., 2007; Bagnardi and Amelung, 2012; Bagnardi et al., 2013; Lundgren and Rosen, 2003; Lundgren et al., 2003; Solaro et al., 2010). Only a limited number of papers have considered the effect of lava cooling on geodetically observed deformation (Stevens et al., 1999; Briole et al., 1997; Amelung et al., 2000; Froger et al., 2004; Pritchard and Simons, 2004; Lu et al., 2005; Tinard, 2007; Fournier et al., 2010; Peltier et al., 2010; Pinel et al., 2011; Toombs and Wadge, 2012; Whelley et al., 2012; Ebmeier et al., 2012, 2014; Caricchi et al., 2014; Parker et al., 2014; Poland, 2014; Odbert et al., 2015) and the vast majority are focused on young deposits. Here, I aim to characterize the deformation associated with emplaced volcanic products after several decades to demonstrate that their contribution to the deformation field can be significant.

After introducing the geological settings, I present the Interferometric Synthetic Aperture Radar (InSAR) time series analysis data and method used to constrain the ground deformation in the vicinity of Parícutin and the results obtained. To isolate the causes of the observed ground motion, the deposits and lava thicknesses are estimated and a model of dynamic cooling is developed. Finally, the implications of the observed deformation are discussed.

2. Geological settings

Parícutin belongs to the Michoacán–Guanajuato volcanic field (MGVF), the largest monogenetic province of Mexico, part of the Trans-Mexican Volcanic Belt (TMVB) (Fig. 1a). The TMVB is a Neogene arc stretching from the Pacific coast to the Caribbean coast (Ferrari et al., 2012) and resulting from the subduction of the Cocos plate under the North American plate at rates of 5 to 6 cm/year, increasing towards the southeast (Ramírez-Herrera and Urrutia-Fucugauchi, 1999) (Fig. 1a). The trench is at an angle of ~15° relative to the orientation of the volcanic belt due to the flat subduction of the Cocos plate (Pérez-Campos et al., 2008). The MGVF is home of over 1400 vents but only two historic eruptions are documented, those of Parícutin (1943–1952) and Jorullo (1759–1774) (Simkin and Siebert, 2002) (Fig. 1a). Parícutin is located north of Cerro Tancitaro and northwest of the city of Uruapan (300,000 inhabitants) (Fig. 1b).

The Parícutin cinder cone grew vertically (up to 424 m) and horizontally by lava and scoria production from the main vent (Fig. 1c). The second and third vents, Sapichu and Taqui, formed later, aligned with the main vent (Fig. 1c), and produced lava and ash to a lesser extent. Such aligned volcanic vents formed by fissuring are typical of cinder cones (Settle, 1979). The total volume of basaltic-andesitic lavas (density of 1.9×10^3 kg/m^3) and pyroclastic material ejected is estimated to be 1.9 km^3 (Fries, 1953). The lava field extends north of the edifice and covers an area of ~25 km^2 following a roughly elliptical pattern with a major axis of 7 km oriented southeast northwest and a minor axis 5 km (Fig. 1c). Parícutin's eruption produced around 40 lava flows with an individual average thickness of 10 m, but highly non-uniform, resulting in the formation of a shield-like topography rising up to 245 m above the pre-1943 surface (De la Cruz-Reyna and Yokoyama, 2011; Rowland et al., 2009), but no precise map of the deposits and lava thicknesses exists.

3. Data and method

I use 2007–2011 Synthetic Aperture Radar (SAR) data from the Advanced Land Observing Satellite (ALOS) of the Japanese Space Exploration Agency (JAXA) made available by the Alaska Satellite Facility

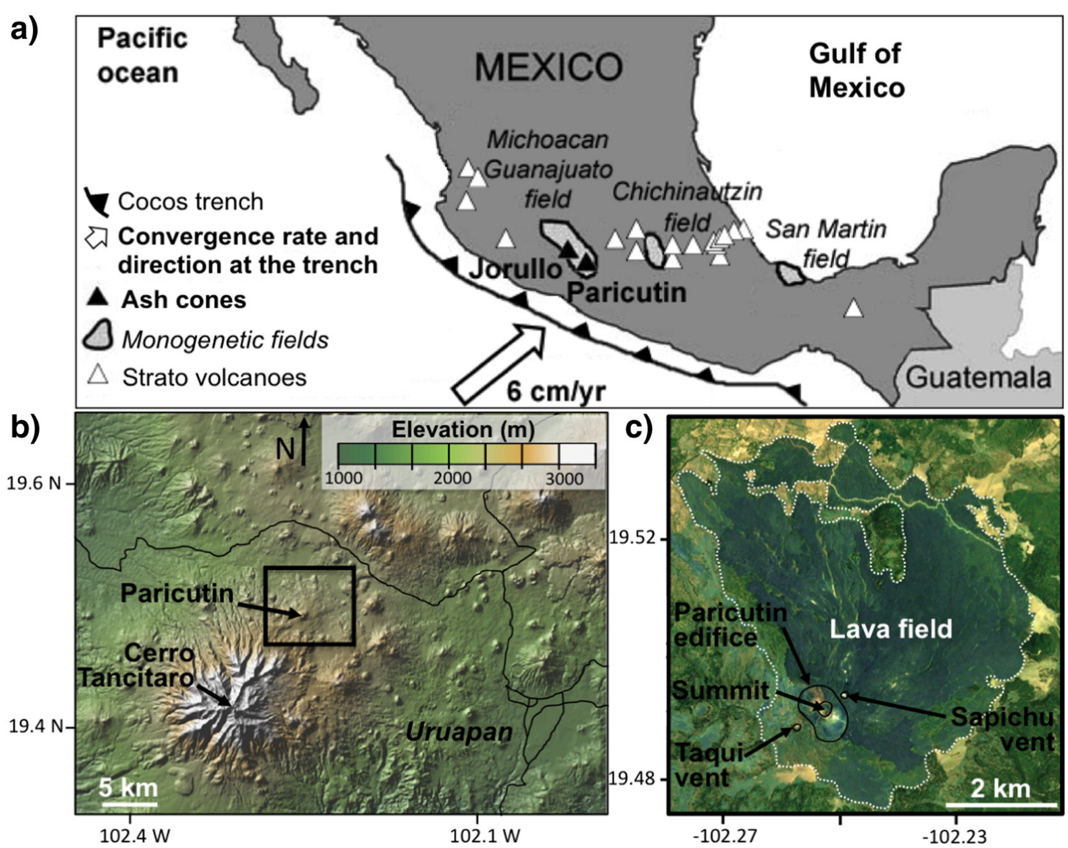

Fig. 1. a) Map of Mexico showing the locations of volcanoes of the TMVB (open triangles) and of the monogenetic fields (gray shapes). Jorullo and Parícutin cinder cones (black triangles) are shown in the Michoacán–Guanajuato monogenetic field. b) Topographic map of the area near Parícutin showing the emplacement of the volcano relative to the main roads (black lines) and the closest city (Uruapan). The black box shows the location of (c). c) Google Earth optical image of the Parícutin area with the main volcanic features indicated. The white pointed line marks the borders of the lava field.