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Time-dependent displacements during and after the April 2007 eruption of Piton de la Fournaise, revealed by interferometric data

Jean-Luc Froger [a,*], Vincent Famin [b], Valérie Cayol [a,c], Aurélien Augier [a], Laurent Michon [b], Jean-François Lénat [a]

[a] Laboratoire Magmas et Volcans, Université Blaise Pascal – CNRS – IRD, OPGC, 5 rue Kessler, 63038 Clermont-Ferrand, France
[b] Laboratoire GéoSciences Réunion, Université de La Réunion, Institut de Physique du Globe de Paris, UMR CNRS 7154, Sorbonne Paris Cité, 15 avenue René Cassin, 97715 Saint-Denis, France
[c] Université de Lyon, Université Jean Monnet, 23 rue du Docteur Paul Michelon, 42023 Saint Etienne, France

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ABSTRACT

From March 30 to May 1 2007, Piton de la Fournaise, La Réunion Island, experienced a major eruptive crisis, characterized by the largest emitted lava volume (210×10^6 m^3) of the 20th and 21st centuries, and by a 340 m deep caldera collapse. The event was captured by InSAR data from the ENVISAT and ALOS-1 satellites. From this data, we computed the EW and vertical components of the displacement that occurred on the entire edifice during the co-eruptive period and in the following months. Our results reveal unusually large and time-dependent displacements of the Central Cone and the Eastern Flank of Piton de la Fournaise, both of which continued to deform for at least a year after the end of the eruption. The analysis of InSAR displacement combined with other geophysical and field observations allows us to propose conceptual models to explain the Central Cone and the Eastern Flank displacements. We propose that the April 2007 caldera collapse induced a sudden decompression of the hydrothermal system, which had been previously pressurized and heated by temporary sealing of its upper part. This sudden decompression resulted in a strong centripetal subsidence. This then decreased exponentially as poro-elastic compaction and creep of the Central Cone propagated from the collapsed rock column to more distal parts of the hydrothermal system. For the Eastern Flank, we propose that the displacement is related to an intrusion within the Grandes Pentes. While propagating to the surface, the intrusion may have encountered a pre-existing structural discontinuity, intruded it and activated it as a detachment surface. It is likely that the detachment slip, by reducing the minimum principal stress close to the summit, allowed the injection of the dyke that fed the brief March 30–31 eruption. Then it may have promoted the migration of magma from the main magma storage zone, beneath the Central Cone, to the distal April 2 eruption site. The EW extensional stress field resulting from the slip of the detachment during the co-eruptive period may have activated a set of normal faults on which aseismic creep controlled the response of the edifice during the post-eruptive period.

1. Introduction

The development of spatial geodetic techniques has brought about considerable advances in the monitoring and interpretation of ground surface displacement in volcanic settings over the last few decades (Dzurisin, 2007). Several studies have looked at static displacements occurring as an immediate response to stress variation, resulting either from the infilling or emptying of a magma source in the upper crust (Pritchard and Simons, 2002; Froger et al., 2007) or from propagation of a magmatic intrusion to the surface (Sigmundsson et al., 1999; Froger et al., 2004; Fukushima et al., 2005, 2010). Time-dependent displacement has also been observed in relation to deep intrusions embedded in a visco-elastic (Newman et al., 2006; Fialko and Pearse, 2012) or elasto-plastic crust (Trasatti et al., 2005), pressurization or depressurization of hydrothermal systems (Rinaldi et al., 2010), volcano-tectonic processes (Palano et al., 2009; Montgomery-Brown et al., 2011), or compaction and loading of lava flows (Stevens et al., 1997).

In this paper, we look at both static and time-dependent ground surface displacements recorded at Piton de la Fournaise (La Réunion hotspot, Fig. 1a–b) during and after the March 30 to May 1, 2007 eruptions.

Piton de la Fournaise has been extensively monitored since 1980 by ground surface displacements (GPS, Electronic Distance Measurement, and tiltmeters) and seismic monitoring networks operated by the Observatoire Volcanologique du Piton de la Fournaise (OVPF). In 2007, the GPS network was composed of 12 continuous GPS stations (Fig. 1c) recording ground surface displacements at 30 s intervals (Staudacher et al., 2009). Piton de la Fournaise is also one of the few volcanoes in the world to be monitored on a regular basis, since 1998, by Interferometric Synthetic Aperture Radar (InSAR) data. Thirty of the 39 eruptions that occurred during the 1998–2010 period were imaged using data provided by the Canadian RADARSAT-1 satellite (Sigmundsson et al., 1999; Fukushima et al., 2010), the European ASAR-ENVISAT satellite (Froger et al., 2004;

* Corresponding author. Tel.: +33 4 73 34 67 69, +33 4 77 48 51 18; fax: +33 4 73 34 67 44.
E-mail address: J.L.Froger@opgc.univ-bpclermont.fr (J.-L. Froger).

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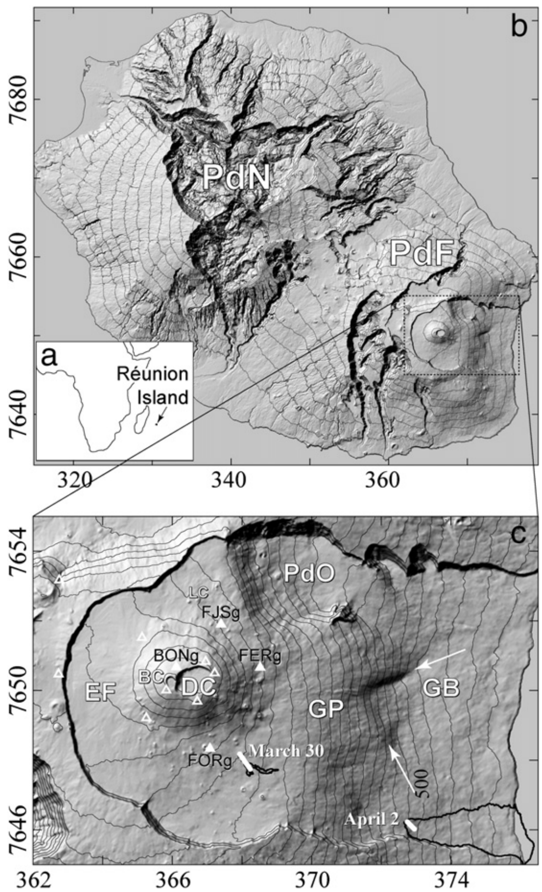

Fig. 1. a) Location of La Réunion Island in the Indian Ocean. b) Location of Piton des Neiges (PdN) and Piton de la Fournaise (PdF) volcanoes. c) Topography of Piton de la Fournaise with 100 m elevation contours and location of the main places discussed in text (BC: Bory Crater; DC: Dolomieu Crater; EF: Enclos Fouqué; GB: Grand Brûlé; GP: Grandes Pentes; LC: Langlois Cone; PdO: Plaine des Osmondes). White triangles indicate the locations of the OVPF GPS permanent stations (filled white triangles indicate the location of GPS stations discussed in text). White arrows indicate the Michon and Saint-Ange (2008) V-shaped structure. The locations of the March 2007 and April 2007 eruptive fissures are indicated by straight white lines, while the lava flow contours are in black. Coordinates are in km UTM (40 zone south).

Tinard, 2007), the Japanese PALSAR-ALOS satellite (Augier et al., 2008), the German TerraSAR satellite (Froger et al., 2011) and the Italian Cosmo-SkyMed satellites (Bato et al., 2013).

While the OVPF's GPS monitoring network, concentrated in the vicinity of the Central Cone (Fig. 1c), gives an excellent record of the evolution of summit displacement that occurred in March–April 2007, it does not provide any constraint on the displacement field over the whole edifice. Using the various acquisition geometries and sensitivities provided by the C-band (5.6 cm wavelength) ASAR and the L-band (23.6 cm wavelength) PALSAR data, we computed the EW and vertical components of the ground surface displacements which occurred over the entire edifice during the March–April 2007 eruptions and in the following months. Our results reveal unusually large and time-dependent displacements of the Central Cone and the Eastern Flank of Piton de la Fournaise, which both continued to deform for at least a year after the end of the eruption. The characterization of such large time-dependent displacement has essential implications not only for risk assessment at the Piton de la Fournaise volcano, but also for the understanding of deformation processes related to magma transfer in general.

2. Geological setting

The Piton de la Fournaise volcano forms the SE half of La Réunion, an oceanic basaltic island in the southernmost part of Mascarene Basin (Indian Ocean), 800 km east of Madagascar (Fig. 1a–b). Most historical eruptions of Piton de la Fournaise occurred in the Enclos Fouqué–Grand Brûlé structure, an EW elongated horseshoe shaped depression (~13 × 10 km) opened eastward to the Indian Ocean (Fig. 1c). Among other hypotheses, it has been proposed that the Enclos Fouqué–Grand Brûlé structure results from a caldera collapse (Chevallier and Bachelery, 1981; Duffield et al., 1982; Bachèlery and Mairine, 1990; Bachèlery, 1995) or from flank collapses (Lénat et al., 1990; Labazuy, 1996; Lénat et al., 2001). Although the question of the Enclos Fouqué–Grand Brûlé structure origin is still debated, the presence of debris avalanche deposits offshore of the Piton de la Fournaise Eastern Flank demonstrates the occurrence of flank destabilisations running down slope to the abyssal plain (Lénat et al., 1989; Labazuy, 1996; Le Friant et al., 2011).

In the upper part of the Enclos Fouqué-Grand Brûlé structure, the Central Cone, built up by the accumulation of volcanic products, exhibits an EW elongated shape, with two pit-craters, the Bory crater to the west and the Dolomieu crater to the east. Joint analyses of ground surface displacements, seismicity and petrology–geochemistry of the lavas have led different authors to infer the presence of a main magma storage zone beneath the Central Cone between 0 and 1000 m above sea level (Lénat and Bachèlery, 1990; Peltier, 2007; Peltier et al., 2009a; Prôno et al., 2009). However, the exact depth, volume and shape of this storage zone are still under debate, as well as the presence of only one or several separate storage units.

After an unusually long period of 63 months rest, on March 1998, Piton de la Fournaise began a new period of activity, characterized by an average rate of 2.7 eruptions per year until the December 2010 eruption. During this period, in most cases the eruptive fissures opened in the summit crater of the Central Cone or occurred directly on the flank of the Central Cone. Exceptionally, fissures opened at low elevation far from the central cone in the Plaine des Osmondes or in the Grand Brulé (Fig. 1c, Peltier et al., 2009a).

3. The March–April 2007 eruptions

The March–April 2007 eruptions were preceded by 10 months of quasi-continuous activity during which 3 summit eruptions took place (July–August 2006, August 2006–January 2007 and February 2007, Peltier et al., 2009a). By the end of this period the Dolomieu crater (Fig. 1c) had become overfilled and lava flows started to spill over the crater rim at its lowest elevation. The first two months of 2007 were marked by a continuous inflation of the both the entire edifice and the Central Cone (Staudacher et al., 2009). Peltier et al. (2009b) interpreted this inflation as evidence of a recharge of the main magma storage zone, generally assumed to exist beneath the Central Cone, between 0 and 1000 m above sea level (Lénat and Bachèlery, 1990; Peltier, 2007; Peltier et al., 2009a; Prôno et al., 2009). A deeper source of inflation was recently proposed from the RER far field very broadband seismic station (Fontaine et al., 2014). Whatever the source's depth, the March–April 2007 eruptions were heralded by a progressive increase in seismicity beneath the summit zone from the end of February to the end of March. On March 30, at 18:50 GMT an eruptive fissure opened at 1900 m above sea level at the southeastern base of the Central Cone (Staudacher et al., 2009). The fissure fed a small lava flow ($<10^6$ m^3, Staudacher et al., 2009, Fig. 1c) of aphyric basalt during an initial, ~10-hour-long, eruptive phase. On April 2 a new eruptive fissure opened 7 km away from the summit on the lower Eastern Flank (~600 m above sea level, Fig. 1c), also emitting aphyric basalt. From April 5, the OVPF seismic and GPS networks recorded a significant increase in activity below the Central Cone (Michon et al., 2007). The crisis climax was reached in the night between April 5 and 6 with the onset of the collapse of the Dolomieu crater. At the same time, a significant increase in eruptive activity was observed at the lower Eastern Flank eruptive fissure, together with an evolution of lava composition toward oceanite (Di Muro et al., 2014). The eruption continued until May 1 with