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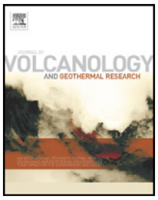

Deep fluid transfer evidenced by surface deformation during the 2014–2015 unrest at Piton de la Fournaise volcano

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ABSTRACT

Identifying the onset of volcano unrest and providing an unequivocal identification of volcano reawakening remain challenging problems in volcanology. At Piton de la Fournaise, renewal of eruptive activity in 2014–2015, after 41 months of quiescence and deflation, was associated with long-term continuous edifice inflation measured by GNSS. Inflation started on June 9, 2014, and its rate progressively increased through 2015. Inflation onset was rapidly followed by an eruption on June 20–21, 2014, showing that volcano reactivation can be extremely fast, even after long non-eruptive phases. This short-lived eruption involved a shallow source (1.3–1.9 km depth below the summit). The inflation that followed, and eruptions in 2015, involved a larger depth range of fluid accumulation, constrained by inverse modeling at ca. 3.9 to 1.2–1.7 km depth. This time evolution reveals that volcano reawakening was associated with continuous pressurization of the shallowest parts of its plumbing system, triggered by progressive upwards transfer of magma from greater depth. A deep magma pulse occurred in mid-April 2015 and was associated with deep seismicity (3 to 9.5 km depth) and CO_2 enrichment in fluids emitted by summit fumaroles. From this date, ground deformation accelerated and the output rates of eruptions increased, culminating in the long-lasting, large-volume, August–October eruption (~36 Mm^3). This evolution suggests that deep magma/fluid transfer through an open conduit system first provoked the expulsion of the top of the plumbing system in June 2014, and then induced the progressive vertical transfer of the entire plumbing system down to 9 km (four eruptions in 2015). The new sustained feeding of the volcano was also at the origin of the hydrothermal system perturbation and the acceleration of the eastern flank motion, which favor lateral dike propagation and the occurrence of frequent and increasingly large eruptions. Our results highlight the fast and progressive way in which basaltic magmatic systems can wake up.

1. Introduction

Basaltic eruptions are often preceded by variable-duration phases of magma and/or fluid migration and accumulation in depth. Such migrations and accumulations, when reaching a given threshold, generate subtle ground deformation, which can be detected by ground-based instrumentation and satellites (e.g. Delaney et al., 1993; Neri et al., 2009; Bonforte et al., 2013; Froger et al., 2004; Peltier et al., 2009; Anderson et al., 2015), seismicity and change in surface gas emission. Time series analysis and inversion of the ground deformation pattern allow recognition of the time and space evolution of the pressurization of the magma storage zone(s), their shape, volume and location, and to make inferences on the timing of magma transfer and accumulation at depth. However, picking the onset of volcano unrest and providing an unequivocal identification of volcano reawakening still remain very challenging.

On the highly active Piton de la Fournaise hot spot basaltic volcano (La Réunion island, Indian ocean), recent advances allow a better understanding of its dynamics (activity and pause periods, inflation/deflation cycles, time evolution of micro-seismicity) and of its plumbing system. Geophysical and geochemical studies converge on the identification of several storage levels, variably connected and distributed over about 10 km below the volcano summit (e.g. Battaglia et al., 2005; Brenguier et al., 2008; Peltier et al., 2009; Di Muro et al., 2014). In the upper levels, several zones of possible magma/fluid accumulation have been proposed in the literature: shallow magma pockets slowly cooling at 0.5–1.5 km beneath the summit craters, as suggested by seismic and deformation features of the volcano during the 1980–1990 period (Bachèlery and Mairine, 1990) and after 2007

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(Peltier et al., 2010; Di Muro et al., 2015); a main shallow reservoir at about 1.5–2.5 km depth evidenced by seismic tomography and deformation data from the 1998–2007 period and capped by a seismic zone (e.g. Nercessian et al., 1996; Peltier et al., 2008; Massin et al., 2011; Prôno et al., 2009); deeper storages at 3.5 km depth (Prôno et al., 2009) and 7.5 km depth (Battaglia et al., 2005) evidenced by seismic tomography and deep earthquake locations. Shallower storage levels feed most of the frequent, small volume summit or near-summit eruptions (e.g. Peltier et al., 2007, 2008), while deeper levels possibly activate during the largest eruptions like the major, summit collapse forming event of April 2007 (e.g. Di Muro et al., 2014; Fontaine et al., 2014).

During the 1998–2011 period of sustained activity, the volcano displayed a mean of 2.6 eruptions per year, characterized by a very large range in emitted volume of lava between <1 Mm^3 and 220 Mm^3 (e.g. Peltier et al., 2009; Staudacher et al., 2009; Roult et al., 2012). During this period, refilling of the shallowest magma storage level (1.5–2.5 km depth) was well evidenced: 1) in 1998, with 35 h of upward earthquake migration from 7.5 km depth to the surface via an almost vertical conduit below the summit's western part (Battaglia et al., 2005); and 2) between 2000 and 2007, with continuous summit inflation linked to the continuous pressurization of a source located at 1.5–2.5 km depth (Peltier et al., 2009). According to geochemical studies, the whole system (from the oceanic crust to the shallow reservoir) was recharged by a new magma input in 2005 (Vlastélic et al., 2007) and 2007 (Di Muro et al., 2014). In 2007, the major pulse of deep magma resulted in the expulsion of 220 Mm^3 of the shallow-seated magmas and in the summit caldera collapse to a depth of 320 ± 20 m (Staudacher et al., 2009). During the period of continuous refilling (2000–2007), eruptive activity occurred in cycles of less than 1.5 years, each of them being characterized by successive summit/proximal eruptions and ending by large distal one, which far propagation, more than 4 km from the summit, was favored by the unbuttressed eastern flank destabilization (Peltier et al., 2008, 2009). These eruptive cycles have been attributed to stress cycles linked to a non-linearity in the stress state of the edifice (Got et al., 2013). This allows the edifice to modulate magma transfer from a constant input rate to discrete, cyclical production of magma at the surface.

A change in this cyclicity occurred after the major eruption of April 2007. From 2007 to 2014, no such obvious refilling has been observed (i.e. summit seismicity was relatively shallow, with the notable exception of the November 2009 eruption, which was preceded by a seismic swarm at about 7.5 km below the volcano summit), and the volcano experienced a sequence of short lived, small volume eruptions and intrusions mostly located inside or around the summit craters (2008–2011; e.g. Peltier et al., 2010; Roult et al., 2012). Small volume eruptions and intrusions in 2008–2011 were followed by a relatively long phase of quiescence of 41 months (Feb. 2011–June 2014) before a reawakening in June 2014. During the quiescent phase, the volcano deflated, background seismicity was limited to a few shallow events per day, and summit low temperature fumaroles emitted S- and CO_2-poor water-vapor-dominated fluids (Di Muro et al., 2012).

In 2014–2015, the volcanological observatory (OVPF — Observatoire Volcanologique du Piton de la Fournaise/IPGP) recorded an increasing activity rate in terms of deformation, seismicity, gas emissions and eruption rate with five eruptions. All these five eruptions, like more than 97% of the eruptive activity of the last decades (Villeneuve and Bachèlery, 2006), occurred inside the ~8 × 13-km-wide Enclos Fouqué caldera, which is an uninhabited natural depression (Fig. 1): June 20–21, 2014 (south-southeast of the Dolomieu crater; 0.4 ± 0.2 Mm^3 of erupted products), February 4–15, 2015 (west-southwest of the Bory crater; 1.5 ± 0.2 Mm^3 of erupted products), May 17–30, 2015 (to the south-southeast; 4.6 ± 0.6 Mm^3 of erupted products), July 31–August 2, 2015 (to the north; 2 ± 0.3 Mm^3 of erupted products), and August 24–October 31, 2015 (to the west-southwest; 35.7 ± 3 Mm^3 of erupted products emitted in 3 successive stages: August 24–October 18, October 22–24, and October 29–31; see location in Fig. 1).

With this regard, 2014 seems to represent the start of a new cycle of activity. This new period and the associated data are thus important and unique in the context of the volcano's recent history and dynamics. In this paper, we report the first detailed analysis of the pre and inter-eruptive deformation sequence recorded by GNSS (Global Navigation Satellite System) during the 2014–2015 unrest period at Piton de la Fournaise. Renewal of volcanic activity, and its associated precursors, provided the opportunity to explore the reawakening of Piton de la Fournaise, as well as the shallow structure of the volcano plumbing system, in regard of the previous researches and cycles of magmatism. The insights gained from these data, combined with earthquake rates and summit gas concentrations, shed light on the variable dynamics of Piton de la Fournaise, which is a laboratory for many other basaltic volcanoes worldwide and give new information into the progressive way in which basaltic magmatic systems can wake up.

2. Methods

2.1. GNSS data

Our aim is to track the early, low-intensity volcano deformation at the beginning of volcano reawakening. The beginning of volcano inflation occurred with a low rate and therefore could not be detected by Interferometric Synthetic Aperture Radar nor on the noisy long-term signals of tiltmeters at Piton de la Fournaise (Peltier et al., 2015a). Consequently, we focused our analysis on the time series recorded by the permanent GNSS network. In 2014–2015, the OVPF permanent GNSS network was composed of 24 receivers located both on the summit cone, on its flanks, and just outside the Enclos Fouqué caldera (Fig. 1). The recent increase in the GNSS receiver density permits an unprecedented high-quality characterization of volcano deformation rates and patterns over the whole Enclos Fouqué sector (e.g. Brenguier et al., 2012; Got et al., 2013; Peltier et al., 2015b).

The receivers deployed in the OVPF GNSS network are 15 Topcon GB1000, 3 Trimble NetRS, and 6 Trimble NetR9, all of which have a sampling rate of 30 s. Daily data files are transmitted to OVPF by Wi-Fi, and solutions are automatically processed with the GAMIT/GLOBK software package (Herring et al., 2010). For the daily calculations, we use i) international GNSS Service (IGS) precise ephemerides; (ii) a stable support network of 20 IGS stations off La Réunion Island scattered around the Indian Ocean islands and coasts; (iii) a tested parameterization of the troposphere; and (iv) models of ocean loading, Earth and lunar tides. Horizontal and vertical accuracies on the studied period are ~0.5 and ~1 cm, respectively. GNSS displacements shown in this paper were corrected from plate motion, deduced from the REUN IGS station located 15 km to the west of the summit and assumed not to be affected by any volcano deformation.

2.2. Inversion modeling

Based on a-priori knowledge on the source shape and medium rheology, numerous ways exist to model deformation. It is well known that in volcanic areas (e.g. Currenti et al., 2010; Gerbault et al., 2012) and especially at Piton de la Fournaise, part of the deformation is plastic (notably in the eastern, continuously sliding volcano flank). Recent works conducted on Piton de la Fournaise (e.g. Got et al., 2013; Carrier et al., 2015) studied the effect of rock rheology and strength on the dynamics of volcanic processes, exploring the role of elasto-plasticity. But to first approximation, we assume that the very low-intensity and linear pre-eruptive deformation of the terminal cone is elastic. So, for simplicity of implementation and to obtain quick solutions and order-of-magnitude source characteristics, we chose, for automatic routines running in near-real time at the OVPF and for this paper, to consider a simple Mogi source in