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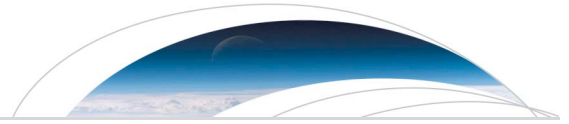
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## RESEARCH LETTER

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## Key Points:

- Tilt change precedes both March and April 2007 Piton de la Fournaise eruptions
- Tilt variation suggests deep magma injection into the volcano plumbing system
- The 2007 eruptions and caldera collapse are related to an inflation-deflation cycle

## Supporting Information:

- Readme
- Text S1
- Figure S1
- Figure S2

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## The 2007 eruptions and caldera collapse of the Piton de la Fournaise volcano (La Réunion Island) from tilt analysis at a single very broadband seismic station

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**Abstract** Seismic records from La Réunion Island very broadband Geoscope station are investigated to constrain the link between the 2007 eruptive sequence and the related caldera collapse of the Piton de la Fournaise volcano. Tilt estimated from seismic records reveals that the three 2007 eruptions belong to a single inflation-deflation cycle. Tilt trend indicates that the small-volume summit eruption of 18 February occurred during a phase of continuous inflation that started in January 2007. Inflation decelerated 24 days before a second short-lived, small-volume eruption on 30 March, almost simultaneous with a sudden, large-scale deflation of the volcano. Deflation rate, which had stabilized at relatively low level, increased anew on 1 April while no magma was erupted, followed on 2 April by a major distal eruption and on 5 April by a summit caldera collapse. Long-term tilt variation suggests that the 2007 eruptive succession was triggered by a deep magma input.

### 1. Introduction

Tilt determined by tiltmeter or broadband seismometer has already been documented for large eruptions [e.g., *Eaton and Murata*, 1960; *Battaglia et al.*, 2000; *Battaglia and Bachèlery*, 2003; *Marchetti et al.*, 2009]. However, caldera collapses are rare events and the triggering processes are mostly inferred from geological, numerical, and experimental approaches [e.g., *Acocella*, 2007; *Holohan et al.*, 2005; *Marti et al.*, 1994, 2008]. Only two recent events of caldera collapse have been monitored by dense geophysical networks: the 2000 Miyake-jima [e.g., *Ukawa et al.*, 2000] and the 2007 Dolomieu caldera collapses [e.g., *Michon et al.*, 2007] in Japan and La Réunion, respectively. On the basis of field, GPS, and seismic data, *Michon et al.* [2007] suggested that the largest historical caldera collapse of the Piton de la Fournaise in 2007 was the outcome of a 7 year long progressive foundering of the shallow plumbing system, combined with the effect of large and fast magma withdrawal during the April 2007 eruption.

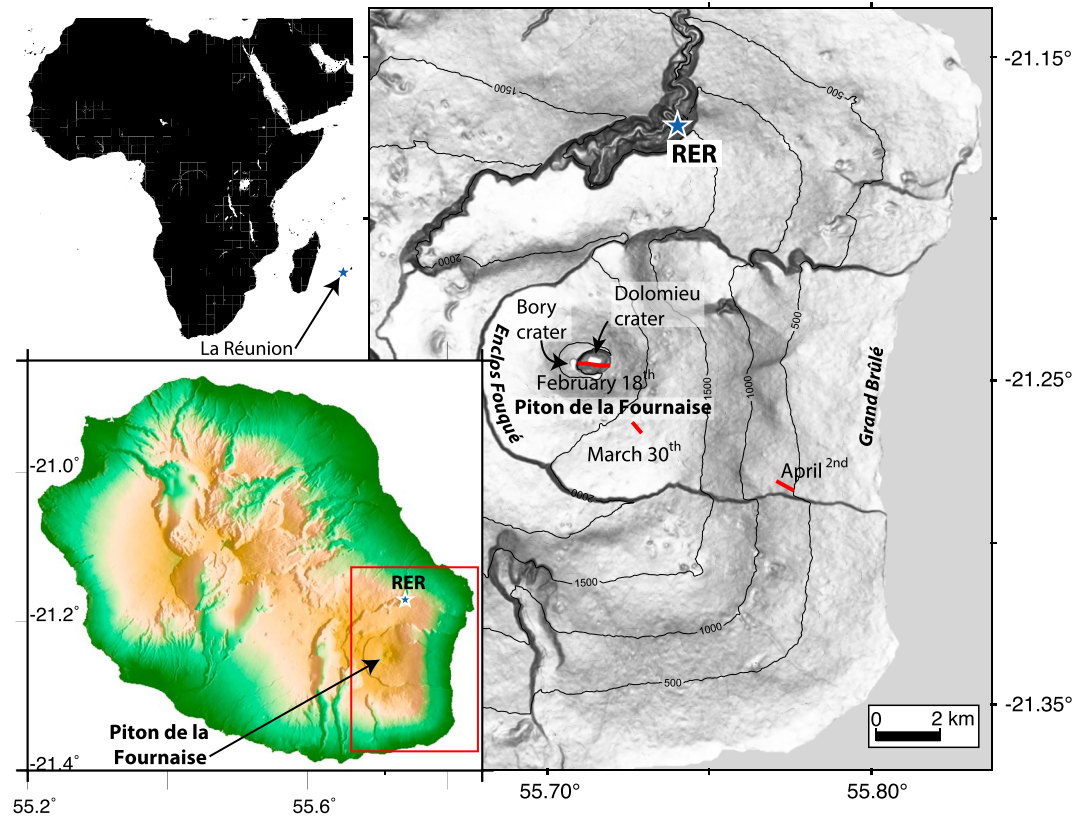
In this paper, we use the Geoscope very broadband seismic station (RER) located on the northern flank of the Piton de la Fournaise edifice to analyze tilt-related signal from 7 November 2006 until 15 May 2007, including the April 2007 major eruption and caldera collapse. *Battaglia et al.* [2000] already showed that RER station displays clear ultra long period signals related to the preeruptive intrusions of the Piton de la Fournaise volcano and suggested that they may have been caused by tilt.

We confirm here that a single, very broadband seismic station is a powerful tool for investigating and potentially monitoring such extreme volcanic events like caldera collapses.

After a presentation of the data collected and of the procedures used to estimate tilt at RER station, we discuss the implications for the understanding of the 2007 eruptive sequence and the related summit caldera collapse.

### 2. The February–May 2007 Eruptive Sequence of the Piton de la Fournaise

The Piton de la Fournaise is a very active basaltic volcano whose central cone is located inside the horseshoe shaped Enclos Fouqué caldera. The cone is capped by two summit craters: Bory and Dolomieu (Figure 1). In April 2007, Dolomieu crater collapsed during the largest historical eruption of the Piton de la Fournaise



**Figure 1.** Location of La Réunion Island in the Indian Ocean. The star indicates the RER very broadband seismic station. The Dolomieu caldera is located at the top of the Piton de la Fournaise central cone on the eastern part of the island. Fissures (red lines) corresponding to the eruptions of 18 February, 30 March, and 2 April 2007 are also indicated.

volcano [Michon *et al.*, 2013]. We summarize below (in Universal Time) the eruptive events succession that led to this major event [Staudacher *et al.*, 2009; Roult *et al.*, 2012].

1. A first short-lived summit eruption took place on 18 February 2007 at 12:35 inside the Dolomieu crater along an east-west trending fissure (Figure 1). The eruption was preceded by a 27 min long seismic crisis located beneath the Piton de la Fournaise summit cone [Massin *et al.*, 2011]. This eruption ended the following day at 21:00, after the emission of less than  $10^6 \text{ m}^3$  of lava.
2. A second eruption started at 19:00 on 30 March, after 2 h and 24 min of seismic crisis. The eruptive fissure opened on the proximal SE flank of the volcano and emitted less than  $10^6 \text{ m}^3$  of lava until its end on 31 March at 3:00.
3. On 2 April at 6:00, a third eruption started at low altitude (590 m), 7 km southeast of the summit. Notably, this event was not preceded by an eruptive crisis below the summit cone, contrary to what is usually observed at the Piton de la Fournaise [Roult *et al.*, 2012]. From 2 April to 5 April, lava was extruded at an unusually high flow rate [Staudacher *et al.*, 2009]. During this period, the seismicity under the summit of the volcano increased gradually. On 5 April, a 7 h long phase of summit deflation occurred synchronously with a further increase in the lava effusion rate [Michon *et al.*, 2007].
4. The first and main collapse step of the summit caldera initiated on 5 April at 20:48 producing a  $M_S$  4.8 seismic event (International Seismological Centre, *Online Bulletin*, <http://www.isc.ac.uk>, Internatl. Seis. Cent., Thatcham, United Kingdom, 2011). The collapse progressed through further 43 steps until 14 April [Michon *et al.*, 2011]. Paroxysmal effusive rate was attained on 6 April. The eruption stopped on 1 May at 20:00. The bulk lava volume emitted during April eruption is estimated to be  $240 \cdot 10^6 \text{ m}^3$  [Roult *et al.*, 2012]. The collapse led to the development of the 340 m deep Dolomieu caldera [e.g., Urai *et al.*, 2007; Staudacher *et al.*, 2009], and the volume of the depression was estimated at  $0.096 \text{ km}^3$  [Urai *et al.*, 2007].

### 3. Data Analysis and Method

#### 3.1. Seismic Recording

In 1986, the Geoscope seismological network installed the three component seismic station RER in a 4.7 km long tunnel, at 8.2 km north of the summit (Figure 1) and altitude of 834 m. The station is equipped with one vertical STS-1V and two horizontal STS-1H seismometers [Wielandt and Streckeisen, 1982] and a Quanterra Q330 digitizer. The corresponding instrumental responses of the Broadband and High gain raw seismic channels (sampling rate 20 Hz) are flat in velocity in the 360 s–0.2 s period range [Roult et al., 2010]. There are no available data for the period 13 to 22 January 2007.

In 2007, this permanent station was the only broadband seismometer installed at La Réunion Island that provided data for the caldera collapse. Previous study demonstrated the good correlation between N-S tilt-related signal, computed at RER station, and tilt recorded from a tiltmeter installed at the same site [Battaglia et al., 2000]. Unfortunately, this tiltmeter had technical problems during the period under study.

#### 3.2. Estimation of Tilt Variation From Seismic Records

The apparent horizontal ground acceleration  $a_x(t)$  observed at RER is likely to be a combination of the true translational ground acceleration  $\ddot{u}_x(t)$  and tilt that may be formalized as  $a_x(t) = \ddot{u}_x(t) - g\tau(t)$  with  $g$  the gravitational acceleration and  $\tau$  the ground tilt. Several studies have reported that broadband horizontal components are sensitive to tilt [e.g., Rodgers, 1968; Aoyama and Oshima, 2008], whereas the influence of tilt on the vertical component is negligible [e.g., Wielandt and Forbriger, 1999; Graizer, 2005]. The tilt contribution may be dominant at frequencies lower than the lower corner frequency of the seismometer ( $f_c$ ) for substantial rotation [e.g., Wielandt and Forbriger, 1999; Pillet and Virieux, 2007]. Ground acceleration obtained from a horizontal broadband seismograph is proportional to tilt if the seismic signal results from tilt only. We used two procedures to constrain the tilt variation in order to check the consistency between their results.

The transfer function of the STS-1 sensor to the ground velocity below  $f_c$  (1/360 Hz) is approximately proportional to the square of frequency. Thus, the tilt signal  $\tau(t)$  can be determined from a time integral of the output voltage of the seismometer by the following equation [Aoyama, 2008; Genco and Ripepe, 2010; Lyons et al., 2012]:

$$\tau(t) = \frac{-Sw_0^2}{g} \int p(t) dt \quad (1)$$

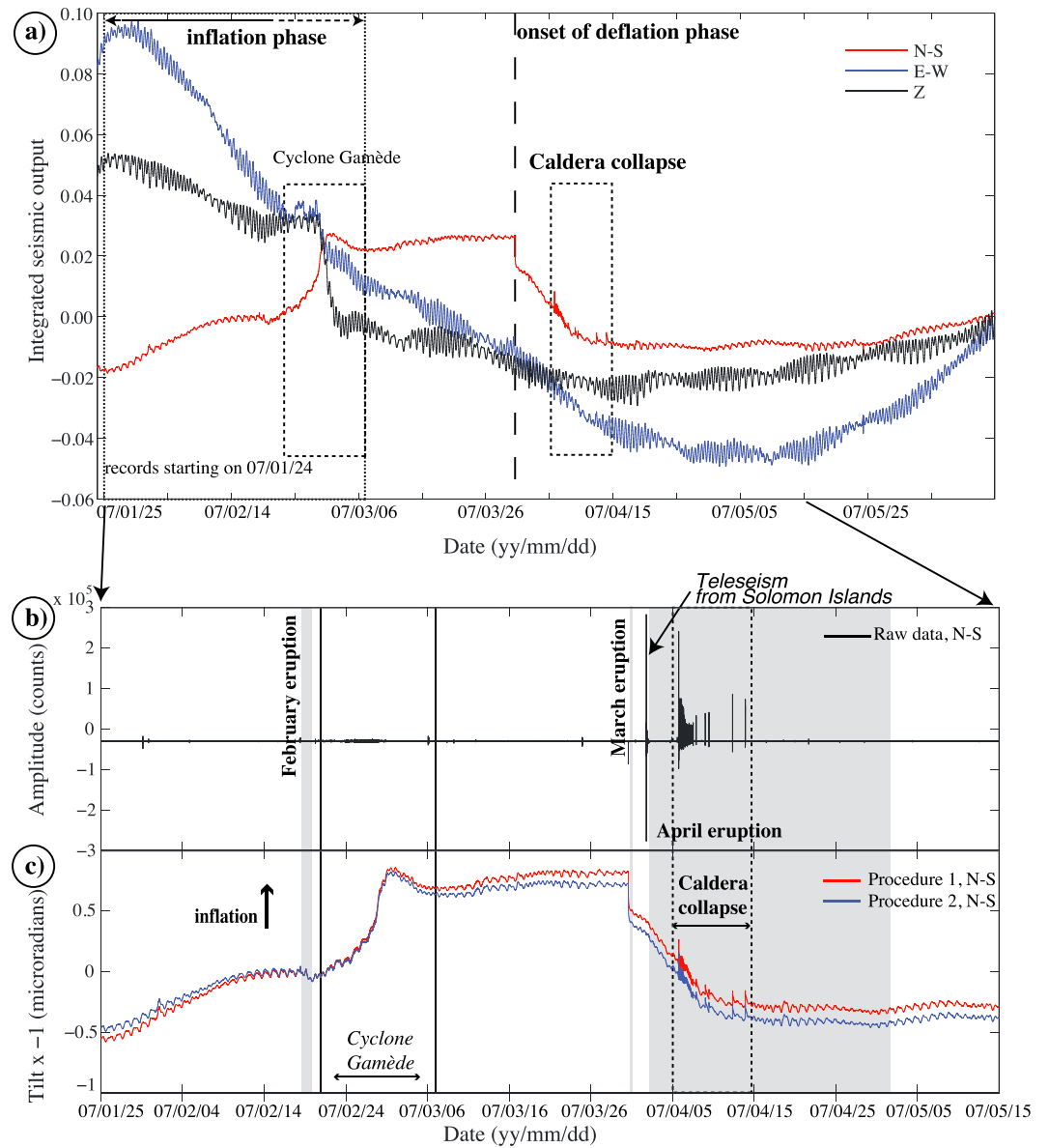
where  $t$  is the time,  $S$  is the seismometer sensitivity,  $g$  is the gravitational acceleration,  $p(t)$  is the output voltage of the seismometer, and  $w_0$  is an angular frequency equivalent to  $2\pi f_c$ . Although the equation includes the contribution of ground acceleration, its effect is regarded as negligible below  $f_c$ .

We followed the similar procedure adopted by Genco and Ripepe [2010] to compute the tilt signal. This was done by (i) removing the mean signal, (ii) integrating the instrument output, (iii) low-pass filtering with a single-pass causal filter below  $f_c = 1/360$  Hz, and (iv) multiplying by  $-Sw_0^2/g$ .

The unfiltered integrated seismometer output of the N-S component, which is quasi radial to the Dolomieu caldera, shows a general increase from late January to beginning of March 2007 followed by a decrease (Figure 2a). The instrumental response was not deconvolved, however, the raw data are multiplied by the sensitivity. A clear long-term decrease started ~2 h before the March eruption. The fact that the vertical component does not show similar variations than the horizontal component and that the time scale of these signals is higher than  $1/f_c$  suggests that they are related to tilt and not to displacement or instrument drift.

For the second procedure, which is similar to that adopted in previous studies [e.g., Battaglia et al., 2000; Wiens et al., 2005], tilt variation is estimated by (i) removing the mean, (ii) low-pass filtering below  $f_c$ , (iii) removing the instrumental response and performing a time differentiation, and (iv) multiplying by  $-1/g$ .

The tilt is multiplied by  $-1$  because the measured tilt at RER has an opposite sign with respect to (i) that measured at the summit during the 2007 caldera collapse [Peltier et al., 2011] and (ii) the expected sign for the 2007 eruptions based on GPS observations [Peltier et al., 2009]. These opposite signs between proximal and distal tilt may be related to the source depth and geometry [McTigue and Segall, 1988; Peltier et al., 2011].

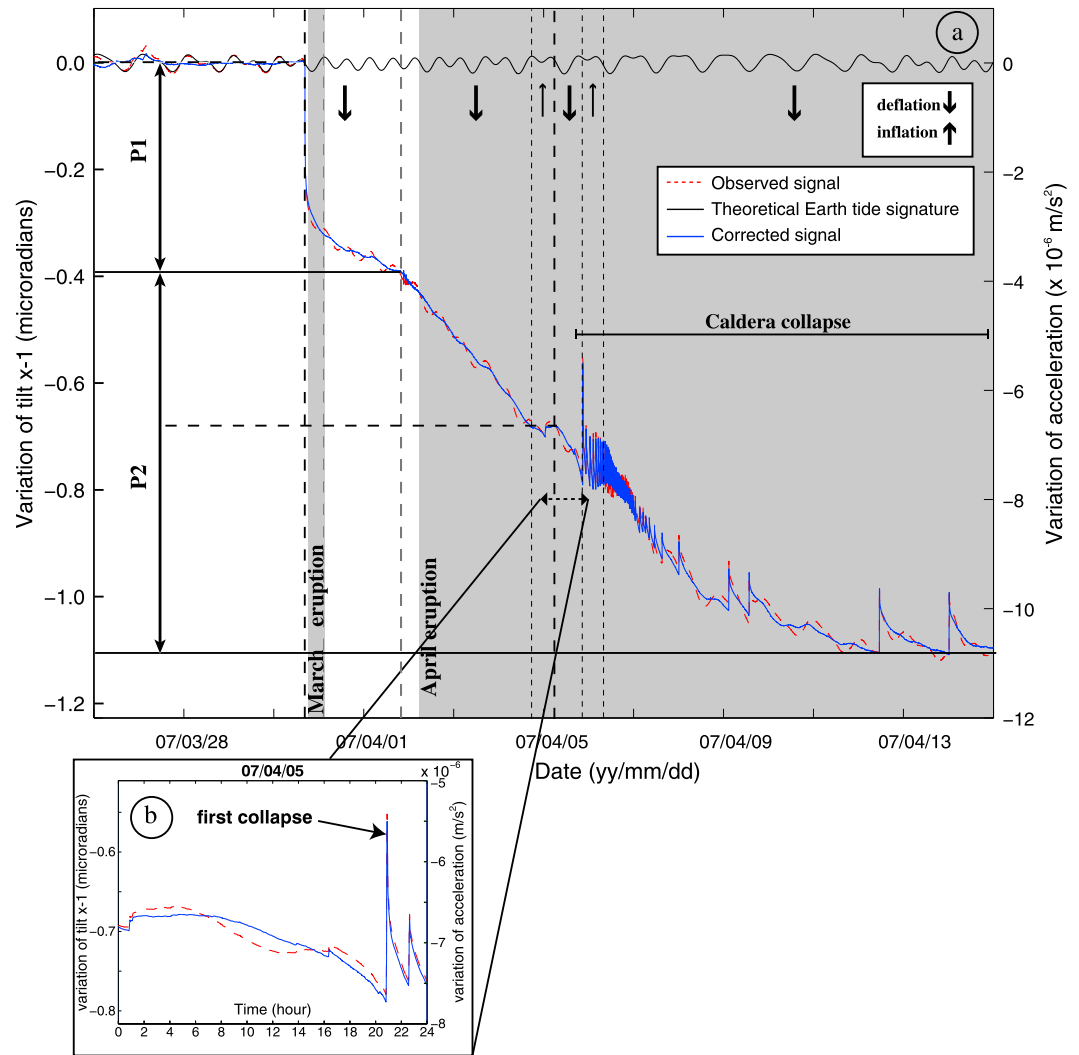


**Figure 2.** (a) Unfiltered integrated seismometer output for the whole 2007 eruptive period recorded at station RER. The Earth tide is observed on the three components. (b) Recording of the N-S component (raw data in counts) for the VH channel. (c) The N-S tilt signals computed at RER from the first and the second procedure. The three 2007 eruptions are indicated in gray (on 18 February, on 30 March, and on 2 April) as well as the caldera collapse and the Gamède cyclone. Two high tides are observed every day.

If long-term variations (over several days) of tilt observed at RER may result from changes in the volcano dynamics, other sources of noise may affect the long-term variations of the records: tropical storms and cyclones, temperature variations and tides (see supporting information for details). They may act as prominent noise sources at ultra-low frequencies.

### 3.3. Cyclone and Tidal Contributions

During the studied period, several storms and cyclones passed close to La Réunion Island. Among these events, only the most intense, named Gamède, which was also the closest one (eye at 230 km North of La Réunion on 25 February), had a significant effect on the observed long-term seismic records (Figure 2).



**Figure 3.** (a) Red trace: estimated tilt signal ( $\mu\text{rad}$ ) of the N-S component from 25 March to 15 April 2007 after applying the second procedure (see text for procedure description). Black trace: theoretical Earth tides tilt computed using the ETERNA software [Wenzel, 1996]. Blue trace: residual seismic signal after removal of the tide effect from the raw data (in red). Vertical right axis gives a conversion of tilt values in terms of acceleration values ( $\text{m/s}^2$ ). Two main phases in the long-term trend of deflation can be identified: P1 and P2. Vertical arrows represent short-term variations of acceleration. Upward: inflation and downward: deflation. (b) Zoomed-in section of the estimated tilt record on 5 April, showing that the main collapse of 5 April at 20:48 was clearly preceded by various discrete tilt steps: at 00:49, 01:03, 13:47, and 16:18.

Tides also affect the amplitude of the seismic signal at frequencies around  $10^{-5}$  Hz. Removing the Earth tide from the seismic records cannot be effective with simple band-pass filtering, due to the characteristics of the seismometer transfer function, which is flat in velocity between  $\sim 0.003$  and 5 Hz but dipping at lower frequencies. The theoretical solid earth tide signature was computed using the ETERNA 3.30 software [Wenzel, 1996] and the most accurate tidal potential catalog [Hartmann and Wenzel, 1995]. This approach allows removal of most of the tidal signature from the observed signal (Figure 3; see supporting information for details).

#### 4. Evolution of the Seismic Signal

Tilts computed from the two procedures show similar results as expected theoretically for frequencies lower than  $f_c$ , with negative values ( $-\tau > 0$ ) corresponding to tilt dipping to the north, i.e., inflation of the edifice (Figure 2c). No clear N-S tilt variation is observed between 7 November 2006 and 12 January 2007



(Figure S1). The long-term tilt of the N-S component indicates an important inflation from 25 January to 20 February, although the signal is strongly influenced by the cyclone Gamède between 21 February and 7 March and, to a lesser extent, the February eruption, which is coeval with only a slight deflation (Figure 2c). The beginning of the inflation may be placed between 13 January and 25 January. Precise identification of the beginning is not possible because of the period of no available data followed by a period of unstable data on 22 January that may be related to technical problem and a period of ground displacement from 23 to 25 January. The ground inflation could have ceased between 20 February and 7 March due to the occurrence of the cyclone Gamède, which perturb the seismograms. Tilt values then remained almost constant until 30 March. At this time, RER station recorded a sudden, large deflation step of around  $0.3 \mu\text{rad}$ , coeval with the onset of the seismic crisis preceding the 30 March eruption. After this step, deflation regularly continued until 1 April 19:52. During this first phase (P1 in Figure 3a), the total deflation reached  $\sim 0.4 \mu\text{rad}$ .

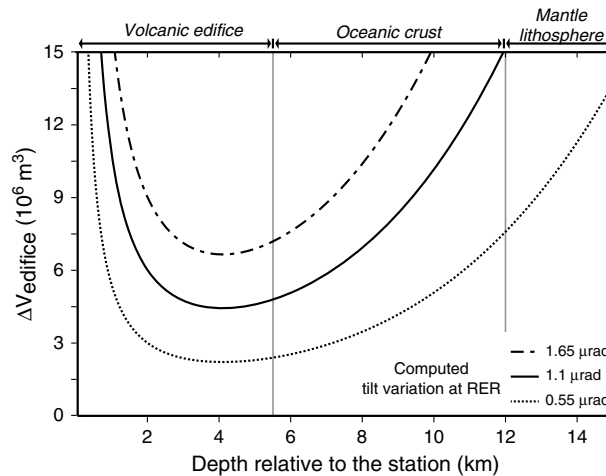
Tilt variation indicates a new deflation increase on 1 April at 19:52, i.e., before the  $M_w 8.1$  Solomon origin time (20:39:56), when neither seismic crisis nor eruption occurred. The first order variation of the tilt signal suggests the occurrence of a second phase of deflation (P2) characterized by an almost constant deflation rate until 8 April at 14:00, followed by a progressive decrease in the deflation rate until 12 April, end of the long-term edifice deflation initiated on 30 March. Notably, deflation stabilized well before the end of the eruption on 1 May. The P2 phase of deflation, which initiated on 1 April, produced a tilt variation of  $0.7 \mu\text{rad}$ . During P2 phase, the edifice experienced two periods of slight inflation indicated by the upward trending arrows (Figure 3a), between 4 April at 17:00 and 5 April at 7:00 and between 5 April at 20:48 and 6 April at 8:00, the second period corresponding to the inflation phase described by Michon *et al.* [2011]. Moreover, RER station recorded every incremental step of the caldera collapse, each step being characterized by a rapid succession of sudden inflation and exponential deflation. Additional short-living, small tilt steps were recorded before the first collapse event (Figure 3b).

## 5. Discussion

### 5.1. Dynamics of the 2007 Eruptive Sequence

Our tilt data indicate that the three 2007 eruptions of the Piton de la Fournaise occurred during a single cycle of edifice deformation, formed by the initial inflation and the later deflation being separated by a 24 days long plateau between 7 March and 30 March (Figure 2). Geochemical data suggest that the 2007 eruptions involved heterogeneous magma compositions from both shallow and deep sources [Di Muro *et al.*, 2014]. Moreover, an interferogram computed from two images acquired on 5 October 2006 and 20 February 2007 [see Froger *et al.*, 2007, Figure 2a] revealed long wavelength fringes west of the Enclos caldera, possibly related to a deep source of deformation. All together, these data are consistent with the injection of deep magma into the shallow plumbing system and suggest that inflation and deflation are linked to a single phase of magma input and output, respectively. We propose that the new deep magma input started in January 2007, triggered the 18 February eruption, which led to a slight edifice-scale deflation and coeval summit inflation [Peltier *et al.*, 2009] superposed to a general inflating pattern, and ended on 7 March. Surprisingly, the large deflation jump in March was associated with the extrusion of a very small lava volume. On 30 March at 16:31, the onset of the preeruptive seismic crisis below the volcano summit and the start of summit deformation recorded by GPS [e.g., Got *et al.*, 2013] were interpreted as related to a lateral eastward magma migration from a shallow reservoir. The large tilt step of about  $0.3 \mu\text{rad}$  recorded at RER supports such interpretation. Most important, our tilt data suggest that lateral magma injection continued after the end of 30 March eruption, culminated on 1 April and remained to a relatively constant level until 8 April. The kinematic continuity since 30 March highlighted by tilt data, combined with interferometric data that show that a large flank deformation area was connected to both 30 March and 2 April eruptive fissures [Clarke *et al.*, 2013], suggests that a single lateral intrusion fed both eruptions. In such a process, the twofold deflation (P1 and P2) may reflect a nonlinear magma migration below the east flank. The overall evolution of the tilt signal also reveals that the caldera collapse did not significantly influence the general edifice deflation since (1) the deflation rate was almost similar before and during the caldera collapse and (2) the deflation stopped before the end of the caldera collapse. We note that short inflation phases occurred just before and during the caldera collapse and during the first nine collapse events. Interestingly, very long period signals possibly due to an inflation source were also observed before the Miyake-jima caldera formation [Kobayashi *et al.*,





**Figure 4.** Tilt change determined at the distance of the RER seismic station (8.2 km) as a function of source depths and  $\Delta V_{\text{edifice}}$ . The minimum value of  $\Delta V_{\text{edifice}}$  to produce the observed tilt variation ( $\sim 1.1 \mu\text{rad}$ ) is  $4.5 \text{ Mm}^3$ .

a pressurized spherical cavity at depth in an elastic half-space. *Cayol and Cornet* [1998] showed that a half-space model could be used when data are recorded sufficiently away from the summit ( $r > 6a$ , where  $r$  is the horizontal distance between the source and the station and  $a$  is the radius of the spherical source), which is the case of RER station. The surface tilt change ( $\Delta\tau$ ) is determined after modification from *Mogi* [1958] [*Johnson, 1992*] by

$$\Delta\tau = \frac{3dr\Delta V_{\text{edifice}}}{2\pi(d^2 + r^2)^{5/2}} \quad (2)$$

where  $d$  is the source depth relative to the station and  $\Delta V_{\text{edifice}}$  is the volume change of the volcanic edifice (i.e., volume of uplift).

We perform a grid search over  $d$  and  $\Delta V_{\text{edifice}}$  to find the values that may explain the measured tilt variation at RER. Figure 4 shows that the total tilt change of  $1.1 \mu\text{rad}$  recorded at RER station requires a minimum  $\Delta V_{\text{edifice}}$  of  $4.5 \cdot 10^6 \text{ m}^3$  corresponding to a source located under the summit at a depth of 4 km below the station, i.e., about 3.2 km below sea level (bsl). From location of earthquakes occurring during the seismic crisis preceding the March 1998 large eruption, *Battaglia et al.* [2005] proposed that this eruption was triggered by a new magma input from a depth about 5 km bsl. Interestingly, the value of  $\Delta V_{\text{edifice}}$  determined at 3.2 km bsl is close to the value expected for a source depth of 5 km bsl:  $5 \cdot 10^6 \text{ m}^3$  and suggests a deep magma input in 2007. Following recent researches, which suggest that a deep magma reservoir possibly exists between the Moho and 1 km bsl [e.g., *Battaglia et al., 2005; Prôno et al., 2009*], we can estimate a  $\Delta V_{\text{edifice}}$  ranging between  $4.5 \cdot 10^6 \text{ m}^3$  and  $15 \cdot 10^6 \text{ m}^3$  (Figure 4). This range of value falls at the lower end of  $\Delta V_{\text{edifice}}$  estimations (up to  $150 \cdot 10^6 \text{ m}^3$ ) from observed tilts for flank eruptions of Kilauea [*Johnson, 1992*].

It has to be noted that  $\Delta V_{\text{edifice}}$  is not necessarily directly equal to the total magma volume injected in the reservoir [e.g., *Johnson et al., 2000*]. The injection of magma is expected to produce a change in volume cavity due to both the expansion of the cavity and the compression of preexisting magma, which accommodates the injection. *Johnson* [1987] estimated that the total magma volume intruded into the reservoir  $\Delta V_{\text{magma}}$  is likely 1.2–4.5 times the value of  $\Delta V_{\text{edifice}}$  for the Kilauea volcano. *Peltier et al.* [2008] proposed that  $\Delta V_{\text{magma}}$  is 2–5 times greater than  $\Delta V_{\text{edifice}}$  for the Piton de la Fournaise volcano based on the similarities between Kilauea and Piton de la Fournaise. Assuming a  $\Delta V_{\text{edifice}}/\Delta V_{\text{magma}}$  ratio between 1/5 and 1 for these two similar basaltic volcanoes, the new magma input  $\Delta V_{\text{magma}}$  in 2007 was in the range  $4.5\text{--}75 \cdot 10^6 \text{ m}^3$ . The deep injected magma volume represented less than one third of the emitted volume of magma ( $240 \cdot 10^6 \text{ m}^3$ ) during the April 2007 eruption. This is consistent with results from geochemical studies that most of 2007 magma was previously stored in the shallow part of the plumbing system of the Piton de la Fournaise [*Di Muro et al., 2014*].

2012]. However, we cannot determine with our results whether these events account for new magma inputs or result from other caldera-related effects [*Michon et al., 2011*].

Finally, total tilt variations related to inflation and deflation phases had similar magnitude, and RER station recovered the preevent tilt value that may reflect a status of mechanical equilibrium of the Piton de la Fournaise edifice.

## 5.2. Modeling the Inflation Process

One of the simplest and most conventional models for determining volume change associated with volcanic activity is the Mogi model [e.g., *Mogi, 1958*]. The tilt is assumed to be caused by

### 5.3. Volcano Early Warning System for Deep Magma Intrusion

A preruptive tilt signal has been detected at RER seismic station before the February–May 2007 eruptive sequence at the Piton de la Fournaise volcano. This signal shows the possibility to generate warnings from tilt estimated at RER station when threshold values of N-S tilt are reached. These warnings may allow enough lead time for determining if a new magma recharge is ongoing, with possible implications for distal and voluminous eruption, which could affect populated areas on the volcano slopes. The approach here described using a distal very broadband station is clearly complementary to the monitoring of dense networks located closer to the volcano summit and it provides the possibility to identify long-term precursors of deep magma inputs. Retrospectively, a similar long-term tilt variation was recorded from 20 November 1996 [see Battaglia *et al.*, 2000, Figure 3], 6 days before a seismic crisis, which was associated with summit deformation. In a way similar to the evolution of tilt described in this study, this preruptive long-term tilt variation may have been related to deep injection of magma. Such deep magma circulation was proposed by Battaglia *et al.* [2005] based on the location of the seismicity preceding the large March 1998 eruption.

## 6. Conclusion

Data from a single very broadband seismic station provide new constraints on the dynamics of the 2007 eruptions of the Piton de la Fournaise volcano and the related summit caldera collapse. The long-term tilt variation indicates that the three 2007 successive eruptions (February, March, and April) and the caldera collapse are related to a single inflation-deflation cycle. A single deep magma injection may explain the observed single cycle of edifice deformation.

We confirm that tilt represents a powerful precursor signal. Observations before both March and April eruptions and the caldera collapse suggest that tilt estimated at RER seismic station could usefully contribute to monitor the activity of the Piton de la Fournaise volcano.

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