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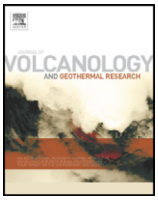

Early detection of large eruptions at Piton de La Fournaise volcano (La Réunion Island): Contribution of a distant tiltmeter station

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ABSTRACT

We report a compilation of data recorded at a distant tiltmeter station (RER) during recent episodes of dyke emplacement and eruption (2003–2007) at Piton de La Fournaise volcano (La Réunion Island). This sensitive station provides useful information for evaluating the extent of deformation. Distinct responses of this station were recorded based on the eruption type. Dykes feeding summit eruptions did not significantly influence the RER tiltmeter signals, whereas dykes feeding large distal eruptions (with vents located more than 4 km from the summit) generated up to 1.4 µrad of tilt, an amplitude 2 to 4 times greater than for proximal eruptions (0.3–0.7 µrad) on the flanks of the summit cone. The distinct tilt amplitude is directly linked to the location, depth, and volume of the dyke. Comparison with summit tiltmeters reveals that up to one-third to half of the RER tilt signal associated to dyke propagation is recorded when the dyke is still below the summit crater. Thus, before large distal eruptions, more than 0.5 µrad of tilt is recorded in less than 20 min when the dyke is below the summit crater (i.e. a few minutes/hours before the beginning of the eruption). We can thus propose for the RER station a threshold value of 0.5 µrad which, when reached as a dyke rises beneath the summit crater, suggests a high likelihood of a large distal eruption. The distant RER tiltmeter station thus appears to be a powerful tool for forecasting the type of eruption that is likely to occur, and can contribute to the early detection of large distal eruptions at Piton de La Fournaise, which are the most dangerous to inhabitants. For volcano monitoring, installation of high precision distant tiltmeters along the lower slopes of a volcano may provide warnings of large eruptions with enough lead time to allow for short-term hazards mitigation efforts.

1. Introduction

In volcanic areas, tiltmeters have long been used to monitor changes in slope associated with eruptions and intrusions (e.g. Dzurisin et al., 1983; Bonaccorso and Davis, 1993; Toutain et al., 1992; Peltier et al., 2005). At Piton de La Fournaise volcano (La Réunion Island, Indian Ocean; Fig. 1a) a tiltmeter network has been in operation around the summit cone since 1980 to monitor the ground deformation associated with the eruptive activity of the volcano. Since 2004, a continuous GPS network has been also implemented (Peltier et al., 2009a). Piton de La Fournaise is one of the most active basaltic volcanoes in the world, with an average of two eruptions per year (Peltier et al., 2009a). The eruptive activity is mainly located either along the N25–30 and N120 rift zones (Michon et al., 2007a) or inside the summit Dolomieu crater (Fig. 1b). On the basis of the location of eruptive fissures, three types of eruption have been distinguished (Peltier et al., 2008, 2009a; Fig. 1b): summit eruptions located inside the Dolomieu crater, proximal eruptions located on the flank or at the base of the summit cone (Fig. 1), and distal eruptions located outside of the summit cone (more than 4 km from the summit). The later eruption type sometimes occurs outside of the Enclos Fouqué caldera threatening the populations living on the north-eastern and the south-eastern flanks of the volcano. The distal eruptions of Piton de La Fournaise are the largest, averaging more than 20 Mm^3, against means of 4 Mm^3 for proximal eruptions and less than 2 Mm^3 for summit eruptions (Peltier et al., 2009a).

Previous deformation studies have shown that dykes feeding each eruption originate from a magma reservoir located at 2200 ± 500 m depth below the summit craters (Peltier et al., 2007, 2008). Other studies based on seismic data (Lénat and Bachèlery, 1990; Massin et al., 2009; Prôno et al., 2009) suggest the presence of additional minor magma pockets (up to ~1000 m depth). Dyke propagation towards the surface generates strong ground displacements (up to 19×10^3 mm d^{-1}) recorded both by GPS (Peltier et al., 2007, 2009a,b), InSAR (Froger et al., 2s004; Fukushima et al., 2005) and tiltmeter (up to 200 µrad; Toutain

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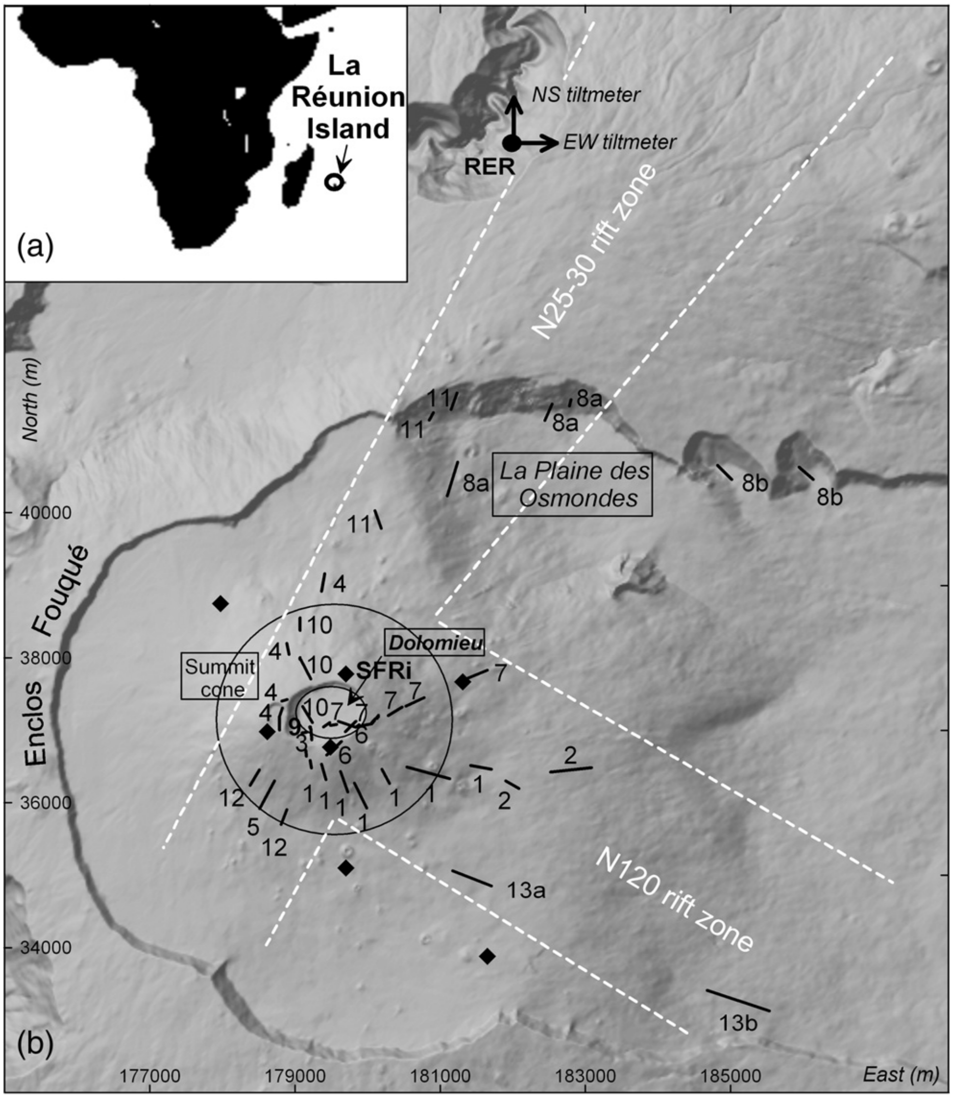

Fig. 1. (a) Location of La Réunion Island (b) Location of the RER tiltmeter station (black arrows represent the orientation of the components), the summit tiltmeters (black diamonds; the labeled SFRi station is the summit station discussed in the text), and eruptive fissures mentioned in the text (black lines). 1: June 11th 2001, 2: November 16th 2002, 3: May 30th 2003, 4: August 22nd 2003, 5: September 30th 2003, 6: December 7th 2003, 7: August 12th 2004, 8a: February 17th 2005, 8b: February 25th 2005, 9: October 4th 2005, 10: November 29th 2005, 11: December 26th 2005, 12: July 20th 2006, 13a: March 30th 2007, 13b: April 2nd 2007. White lines define the N25–30 and N120 rift zones.

et al., 1992; Peltier et al., 2005). These deformation data are used in inverse modelling to infer the location and the geometry of the dykes (Battaglia and Bachèlery, 2003; Froger et al., 2004; Fukushima et al., 2005; Peltier et al., 2007, 2008). Study of continuous ground deformation data (GPS and tilt) highlighted that each dyke propagates first vertically below the Dolomieu summit crater for 10 to 40 min before propagating towards one of the flanks of the volcano in the case of the proximal and distal eruptions (Toutain et al., 1992; Peltier et al., 2005, 2007).

The limitation of the current deformation monitoring networks, which are mainly located around the summit cone, is the lack of distant stations to constrain dyke propagation far from the summit. Distal eruptions are the most dangerous for inhabitants, and it is therefore important to detect them before they erupt. The only distant deformation monitoring station is the RER tiltmeter, located about 8 km northeast of the summit (Fig. 1b). This station provides information concerning the extent of deformation outside of the summit area. The aim of this study is to compare the subtle signal recorded at the RER titlmeter station just before and during thirteen eruptions and one intrusion in the 2001–2007 period in order to discriminate between signals associated with each type of eruption, and also to attempt to identify precursors of major distal eruptions, which are potentially the most dangerous to inhabitants.

2. Tiltmeter network

The deformation network of the Piton de La Fournaise Volcano Observatory includes eight tiltmeter stations. Seven stations are located around the summit cone, either at the top or at the base, whereas one station, RER, is located far away, outside of the Enclos Fouqué caldera, 8 km from the summit, at 800 m elevation (Fig. 1b). Each of these stations is composed of two Blum-type pendulum tiltmeters, one radial and the other tangential to the summit. At RER, the radial and tangential tiltmeters are orientated north–south and east–west, respectively. Blum tiltmeters are astatic mechanical pendulums with a short base and are made of fused silica (Blum, 1963). Each tiltmeter is fixed on a silica base with two levelling screws and is lying directly on a concrete base. The slope variations are recorded at a rate of one sample per min, and the combination of the two components gives the direction and intensity of the tilt in real time. Contrary to other stations which are installed on the surface or inside old lava tubes, the RER station is located in a closed vault, which is itself located in a 4.7 km-long tunnel. This insulated environment provides high thermal stability, with temperature variations less than 0.5° per day (Fig. 2a), and the daily variations recorded by the tiltmeters are less than 0.4 μrad (Fig. 2b). These tilt daily variations are attributed to Earth tide effects, temperature and pressure changes within the vault, and rock dilatation caused by temperature variation outside the vault. The high precision RER tiltmeters (0.02 and 0.03 μrad mV^{-1} for the EW tiltmeter and the NS tiltmeter, respectively) and the thermal stability of the vault allow this station to record subtle signals linked with the eruptive activity. In April 2001, the RER tiltmeters were adjusted and reoriented (i.e., to north–south and east–west orientations; Fig. 1b). The location of the tiltmeters implies that the NS component, closer to radial from the summit than EW component, should have the largest volcanic signal, but unfortunately it was not working during the studied period. Aluminum sulfate deposits have been discovered on the NS tiltmeter magnet in 2007. Even if the magnet does not influence the pendulum stability; such deposits could disturb the pendulum velocity. So no robust observation and conclusion can be made on the signals recorded by the NS tiltmeter. However, the EW tiltmeter and the data acquisition system have been checked; they work well and the tiltmeter is well-coupled to the ground; that is why we only based our discussion on the EW tiltmeter.

We present in this paper only the data recorded by the new tiltmeter configuration made in April 2001. In this study, the time of the RER tiltmeters was calibrated with the time of the RER GEOSCOPE (http://geoscope.ipgp.fr/) very broadband (VBB) seismic station, located in the same vault.

3. RER tiltmeter data

Between 2001 and 2007, thirteen eruptions (three summit, seven proximal, and three distal) and one intrusion were monitored by the RER tiltmeter station. Due to technical problems, data are not available for six additional eruptions (March 2001, January 2002, January 2004, May 2004, August 2006–January 2007, February 2007).

Fig. 2 displays one year of continuous recording, free of interruptions and technical problems, at the RER station in 2003. An annual oscillation of ~9 μrad was recorded on the EW tiltmeter whereas a constant negative drift of ~15 μrad over the course of the year was recorded on the NS tiltmeter (Fig. 2b). Regarding the correlation between the seasonal EW tiltmeter drift and the seasonal temperature variation, we explain the annual oscillation on the EW tiltmeter by the seasonal temperature variation within the vault (Fig. 2a) and rock dilatation caused by temperature variation outside the vault. On the other hand, the negative drift recorded on the NS tiltmeter since 2001 is probably caused by an instrumental drift or a local site effect. The RER station is located close to a 900-m-high cliff (Fig. 1b) and, since its reorientation in 2001, the NS axis is approximately perpendicular to a bend in this morphological discontinuity. The negative drift could be due to slow displacement of the nearby cliff. Indeed a slow displacement of the cliff to the south has been reported by EDF, the French energy company, exploiting the tunnel where the tiltmeters have been implemented. Because of this long-term background noise recorded on the both components, no significant long-term (>1 month) volcanic signal can be discriminated. Nevertheless, signals can be detected minutes to hours before some eruptions (Table 1). Tilt variations monitored by the RER

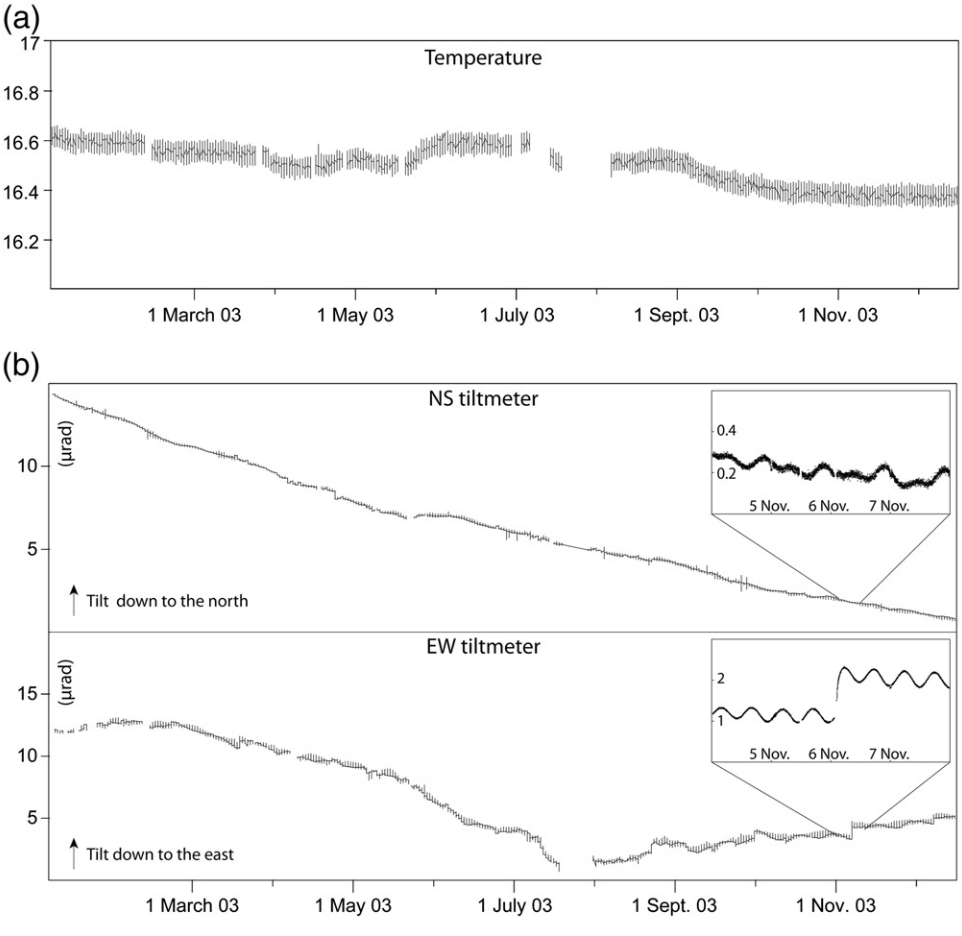

Fig. 2. One year of (a) temperature and (b) tilt variation recorded in 2003 on the RER station.

Table 1
Characteristics of the studied eruptions. Total tilt variation recorded on the EW tiltmeter of the RER station recorded just before recent eruptions at Piton de La Fournaise. For the tilt, positive values correspond to tilt down to the east. Volume of lava flows during each eruption is reported.

Start of eruption	Type of eruption	Location	RER EW tilt during propagation below the summit[a] (μrad)	Total RER EW tilt (μrad)	Emitted volume (10^6 m^3)
11-June-01	Proximal	N120–SE flank	0.13	0.65	9.5
16-Nov.-02	Proximal	N120–SE flank	0.14	0.68	8
30-May-03	Summit	Dolomieu crater	0	0	1.28
22-Aug.-03	Proximal	N25–N flank	0.16	0.4	6.2
30-Sept.-03	Proximal	N25–S flank	0.15	0.36	1
6-Nov.-03	Intrusion	N120–SE flank	Not enough data	0.81	–
7-Dec.-03	Summit	Dolomieu crater	0.28	0.28	1.2
12-Aug.-04	Proximal	NE flank	0	0.55	20
17-Feb.-05	Distal	N25–Plaine des Osmondes	Not enough data	1.35	18–20
4-Oct.-05	Summit	Dolomieu crater	0	0	1.5
29-Nov.-05	Proximal	N25–N flank	0.05	0.41	1
26-Dec.-05	Distal	N25–Plaine des Osmondes	0.5	1.3	15–20
20-July-06	Proximal	N25–S flank	0.18	0.31	2.5–3
30-March-07	Distal	N120–SE flank	0.8	1.39	140

[a] Deduced from Fig. 6.

station before each eruption are reported in Figs. 3, 4, 5, and in Table 1. Given the distance between the eruptive vents and the RER station, the signals were weak on the RER station (1.4 μrad maximum, Table 1), but distinct behaviors can be identified according to the type of eruption.

3.1. Summit eruptions

Before and during summit eruptions (i.e., inside the Dolomieu crater), no or only very small signals were recorded by the RER tiltmeters (Fig. 3, Table 1). Only a weak tilt down to the east (0.3 μrad) was recorded by the RER EW tiltmeter at the beginning of the December 2003 eruption, which occurred in the western part of the Dolomieu crater (see Fig. 1b for location). Contrary to the May 2003 and October 2005 eruptions, one of the two fissures opened on December 7, 2003 was located outside of the Dolomieu crater (Fig. 1b), but it did not emit magma; only gas was released from this fissure during the first day of the eruption.

3.2. Proximal eruptions

A few minutes before proximal eruptions (June 2001, November 2002, August 2003, September 2003, August 2004, November 2005, and July 2006), and also during the proximal intrusion of November 2003, a tilt down to the east is apparent on the RER EW tiltmeter (Fig. 4). The tilt signal onset is 10 to 280 min before the beginning of the eruption and magnitude varied between 0.3 and 0.7 μrad (Table 1, Fig. 4). The highest signals on the EW tiltmeter were recorded just before proximal eruptions located along the N120 rift-zone (i.e., June 2001, November 2002).

Except in June 2001, no significant signal was recorded on the RER NS tiltmeter associated with proximal eruptions (Fig. 4). But due to aluminum sulfate deposits discovered on the NS tiltmeter magnet in 2007 and even if this signal began at the same time as a down-to-the-west of ~0.7 μrad (Fig. 4a), it is not excluded that the down-to-the-north signal of ~0.6 μrad recorded two days before the June 2001 can be a drift signal.

3.3. Distal eruptions

Three distal eruptions were monitored by the RER tiltmeters during the study period (Fig. 5; data are not available for two additional distal eruptions of the 2001–2007 period, in January 2002 and January 2004, due to technical problems). The highest tilt variations detected on the RER EW tiltmeter (>1 μrad) during 2001–2007 preceded the distal eruptions, which were located at low elevations on the northern (February and December 2005) and southern (March–April 2007) flanks. A tilt down to the east began typically 130 to 170 min before the onset of these three distal eruptions. In December 2005, the signal on the EW tiltmeter reversed five hours (15:44) after its onset, resulting in a net tilt down to the west (Fig. 5b). Over the course of the December 2005 eruption, a slight continuous tilt down to the east was also recorded (Fig. 5b).

For the two distal eruptions of February and December 2005, which were located in La Plaine des Osmondes (see Fig. 1b for location) a down-to-the-north signal was also recorded on the RER NS tiltmeter (0.6 and 0.2 μrad in February and December 2005, respectively; Fig. 5a, b, Table 1). The tilt down to the north began two days before the eruption in February 2005 and at the same time as the beginning of a 0.6 μrad of tilt down to the east, whereas it began at the beginning of the seismic crisis (i.e., 130 min before the eruption) in December 2005. But as observed in June 2001, this NS tilt signal needs to be taken into

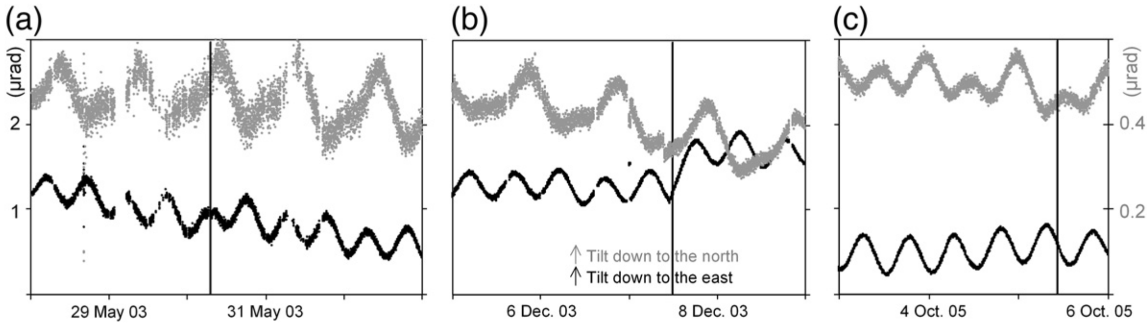

Fig. 3. Tilt variation recorded on the RER EW (black) and NS (grey) tiltmeters during the summit eruptions of (a) May 2003, (b) December 2003 and (c) October 2005. Black lines represent the beginning of the eruptions. For clarity, the scale is distinct for the EW and NS tiltmeters.

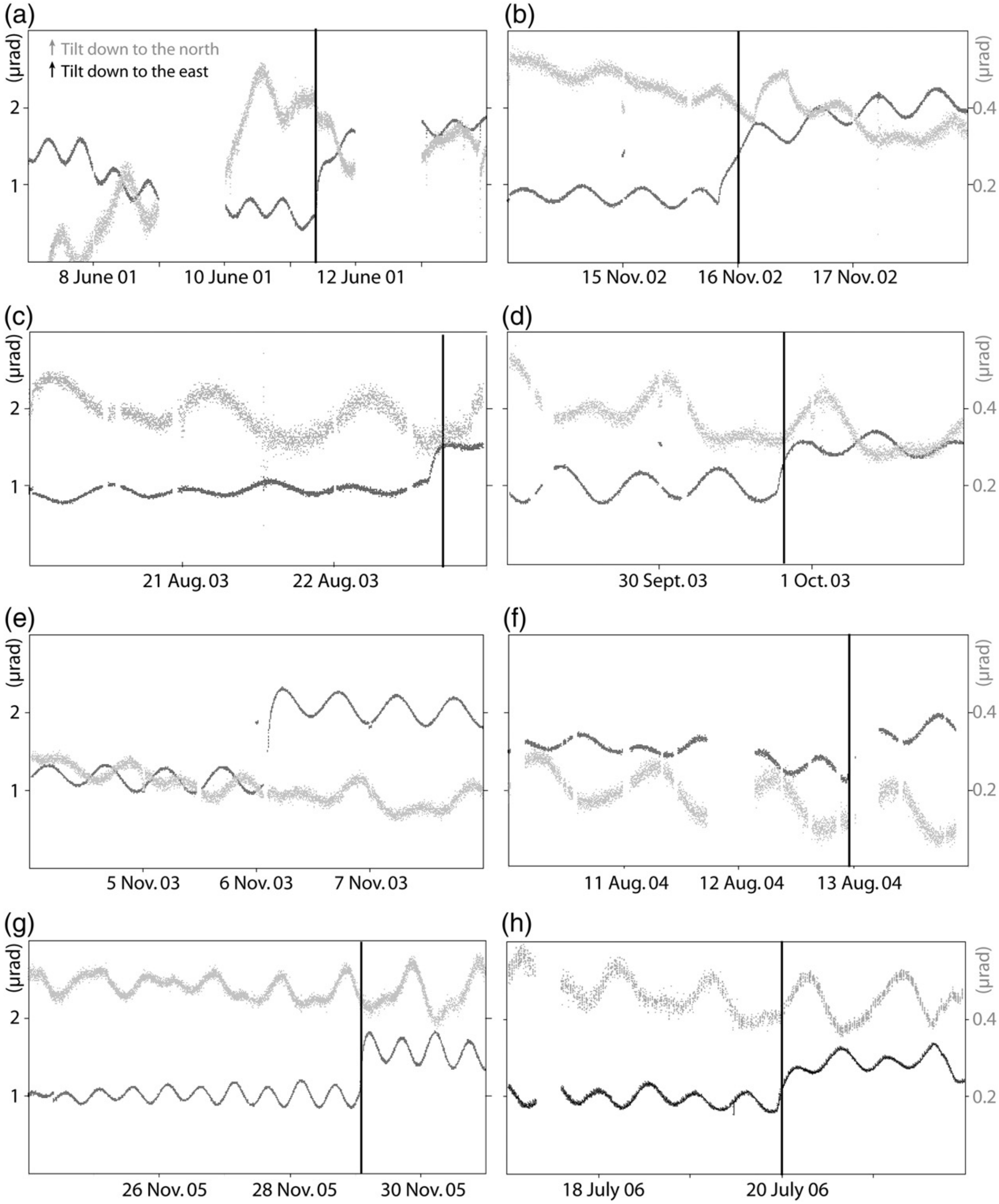

Fig. 4. Tilt variation recorded on the RER EW (black) and NS (grey) tiltmeters during the proximal eruptions of (a) June 2001, (b) November 2002, (c) August 2003, (d) September 2003, (f) August 2004, (g) November 2005, (h) July 2006 and during the intrusion of (e) November 2003. Black lines represent the beginning of the eruptions. For clarity, the scale is distinct for the EW and NS tiltmeters.

consideration carefully because of the aluminum sulfate deposits discovered on the NS tiltmeter magnet in 2007.

On April 1, 2, 5 and 6, 2007, disturbances of the signal were recorded at the two RER tiltmeters (Fig. 5c). These spikes (up to 2–3 µrad on April 1) are generated by the strong seismic activity preceding the resumption of the eruptive activity on April 2 and accompanying the Dolomieu summit crater collapse on April 5 and 6. According to Michon et al. (2007b), Peltier et al. (2009b) and Staudacher et al. (2009), the Dolomieu crater collapse occurred by successive collapse events between April 5 and 6. Each collapse was preceded on the RER station by 30–60 min of tilt down to the east followed by a nearly instantaneous tilt down to the west (0.2–2 µrad) and was accompanied by disturbances of the NS signal (Fig. 5c, d).

4. Comparison between RER and summit tiltmeter data

Before all eruptions, summit tiltmeters detected rapid tilt variations. These signals have been described in previous papers (Toutain et al.,

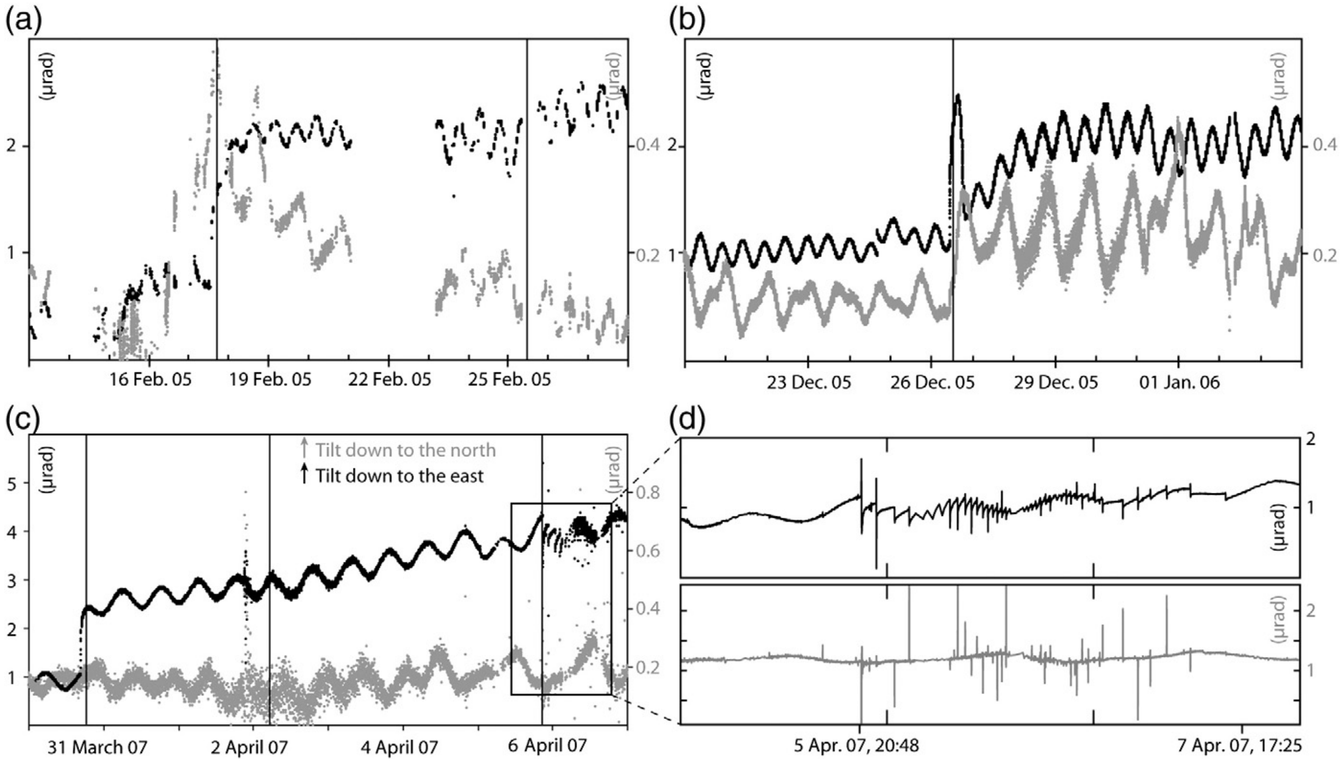

Fig. 5. Tilt variation recorded on the RER EW (black) and NS (grey) tiltmeters during the distal eruptions of (a) February 2005, (b) December 2005, (c) March–April 2007 and (d) on April 5 to 7, 2007. First black lines represent the beginning of the eruptions. For the February 2005 eruption, the second black line represents the fissure opening at low elevation on February 25 (see Fig. 1B for location). For the March–April 2007 eruption, the successive black lines represent the opening of the first eruptive fissure on March 30th, the opening of the last eruptive fissure on April 2nd and the beginning of the Dolomieu crater collapse on April 5th, respectively. For clarity, the scale is distinct for the EW and NS tiltmeters.

1992; Peltier et al., 2005, 2007, 2009a) and have been attributed to dyke propagation towards the surface. The signals recorded by the summit tiltmeters were high (up to 400 µrad; Fig. 6) due to the proximity of the dykes, which always initiated below the summit before propagating towards one of the flanks of the volcano for the proximal and the distal eruptions. The beginning of such lateral dyke propagation is discernible on the NS tiltmeter of the SFRi station (Fig. 6). A tilt down to the north, associated to summit inflation, was recorded at SFRi during the first stage of dyke propagation, whereas a tilt down to the south, associated to summit deflation, was recorded when the dyke propagated away from the summit toward one of the flanks.

The signals on the RER tiltmeters, described in the previous sections, appear in the same time or within a few minutes of the summit deformation pattern linked with dyke propagation (Fig. 6). Comparison between the two datasets allows us to better describe the origin of the RER tilt. For instance, about one sixth to half (one-third to half for distal eruptions) of the RER tilt variation occurred during the first stage of the dyke propagation, when the dyke was still below the Dolomieu crater and before the start of lateral propagation as inferred from summit tilt data (Fig. 6, Table 1).

The tilt down to the east recorded at RER before the proximal and distal eruptions suggests a distant influence of either an inflation source located west of the station or a deflation source located east of the station. The probably out of service NS tiltmeter did not record such subtle variation and, consequently, we are not able to determine the exact location of the pressure source. Regardless, the excellent temporal time correlation between the tilt signals recorded at the summit and RER suggests the influence of a common pressure source. We therefore attribute the RER tilt variations in the minutes–hours before eruptions to a distant effect of shallow dyke propagations towards the surface and south–west of RER.

By contrast, Houlié and Montagner (2007) have attributed the signal extracted from the RER GEOCOPE VBB seismic station, located in the same vault, to a deflating spherical source located south–west of the station. Such a deflating source is not compatible with the tilt signal recorded at the RER tiltmeter station. To conclude to the influence of a deflating spherical source, Houlié and Montagner (2007) have extracted horizontal displacements from the RER GEOSCOPE VBB seismic station but according to Battaglia and Cayol (2009), at long and ultra-long periods, in the near field, the recordings of horizontal seismic components may dominated by tilt effects and the transients cannot be transformed into displacements.

5. Discussion

5.1. Dyke propagation signal: influence of the location, depth and volume

The study of the RER signal, coupled with the summit tiltmeters, indicates that the RER station records the distant influence of an inflating dyke that initiates below the summit crater.

Several parameters can explain the distinct amplitude of tilt variations recorded at the RER station before each type of eruption. Fig. 7 shows the relation between the tilt variations recorded at the RER EW tiltmeter during dyke propagation versus the dyke pathway, the length of the dyke and the erupted volume.

5.1.1. Influence of the dyke pathway

The strongest RER signals (more than 1 µrad of tilt down to the east) occurred during dyke propagations prior to distal eruptions. For dykes that propagated towards the eastern flank of the volcano, the EW tilt component shows the most variation (Fig. 7a). Two of the three distal eruptions (February and December 2005), were located in La Plaine des Osmondes, less than 4 km south of the RER station (Fig. 1b), suggesting a relation between the intensity of the RER tilt and the dyke location. The February and December 2005 eruptive fissures were located in the same area, but a distinct signal was

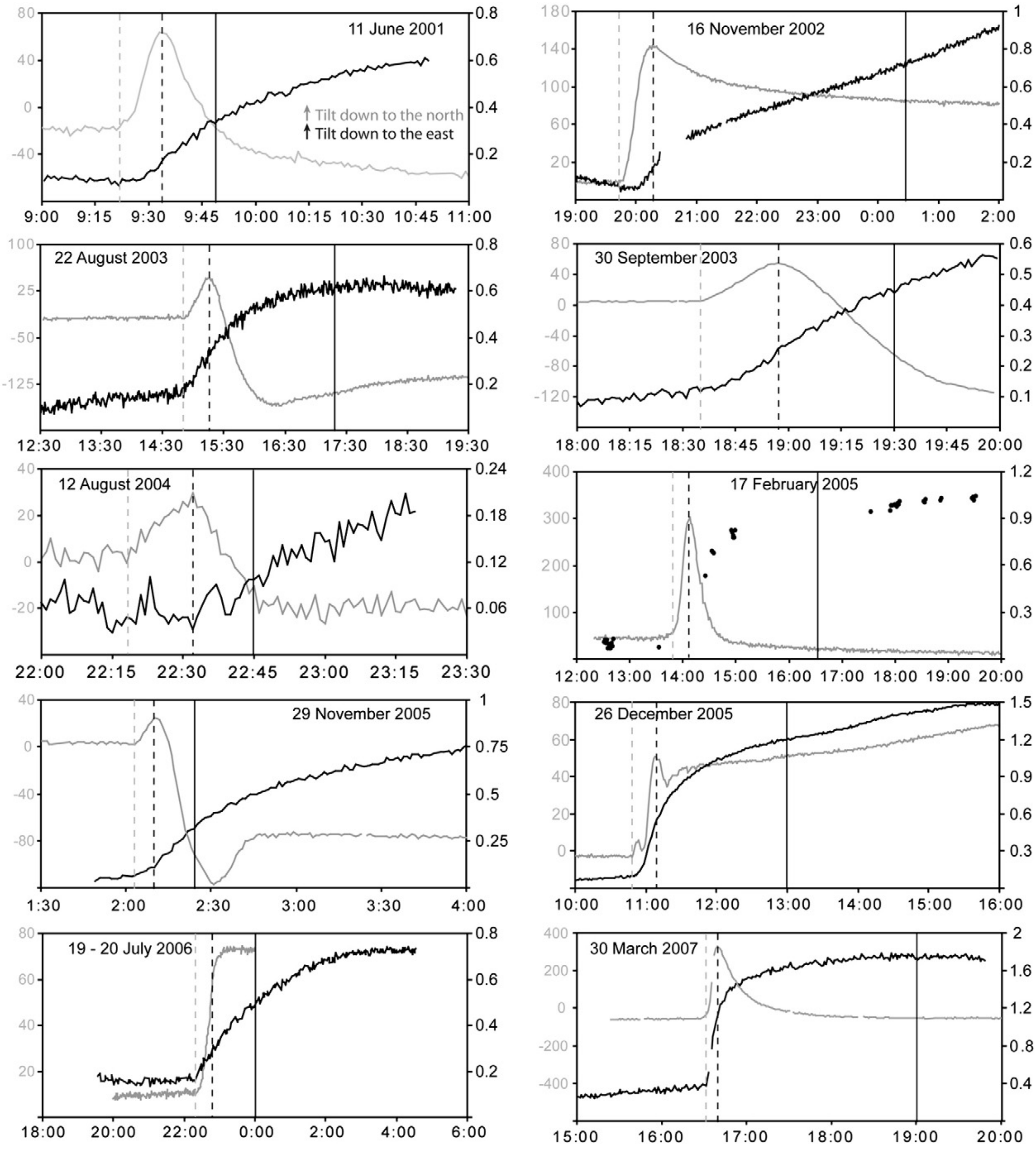

Fig. 6. Comparison between tilt variations recorded on the EW tiltmeter of the RER station (black) and on the NS tiltmeter of the SFRi station (grey), located at the summit of the volcano during proximal and distal eruptions. Summit eruptions, not associated with a lateral dyke propagation towards volcano's flank nor with a significant tilt at RER, are not shown. Grey dashed lines, black dashed lines and full black lines represent the beginning of the tilt at SFRi, the beginning of lateral dyke propagation deduced from the summit tiltmeters, and the onset of eruption, respectively.

recorded at the EW RER tiltmeter. In December 2005, reversal of the signal on the EW tiltmeter after five hours indicates the approach of the dyke towards the RER station. In theory, a reverse of the tilt signal in the direction parallel to the dyke elongation can occur when the dyke passes the projection of the station onto the line of the dyke (Bonaccorso and Davis, 1993). In December 2005, even if the eruptive fissures were located along the cliff of the Enclos Fouqué caldera in La Plaine des Osmondes (Fig. 1b), the front of the dyke propagated outside the caldera cliff (Peltier et al., 2008) and could reach a distance, close to the RER station where the influence of the lateral propagation of the dyke, east of the station, was detectable.

Even if some of the tilt variations recorded during dyke propagation can be attributed to the approach of the dyke towards the RER station, the entire signal cannot be only attributed to the dyke location and orientation. Indeed, no clear relation exists between the intensity of the EW tilt variations and the distance of the eruptive fissures from the RER station (Fig. 7a). For example, during the dyke injection of March 2007, located on the volcano's southern flank, the tilt variations recorded at RER station were the highest (1.4 µrad) even though the dyke propagated away from the station (Fig. 7a). Moreover, about one sixth to half of the tilt signal was recorded during the first stage of dyke propagation, when the summit tiltmeters indicated that the dyke was still below the summit zone (Fig. 6 and Table 1); so the distinct tilt magnitude (up to 0.8 µrad for the distal eruptions) recorded during the first stages of dyke propagations (Table 1) is not related to the dyke location. On the other hand, the dykes that generate the strongest tilt

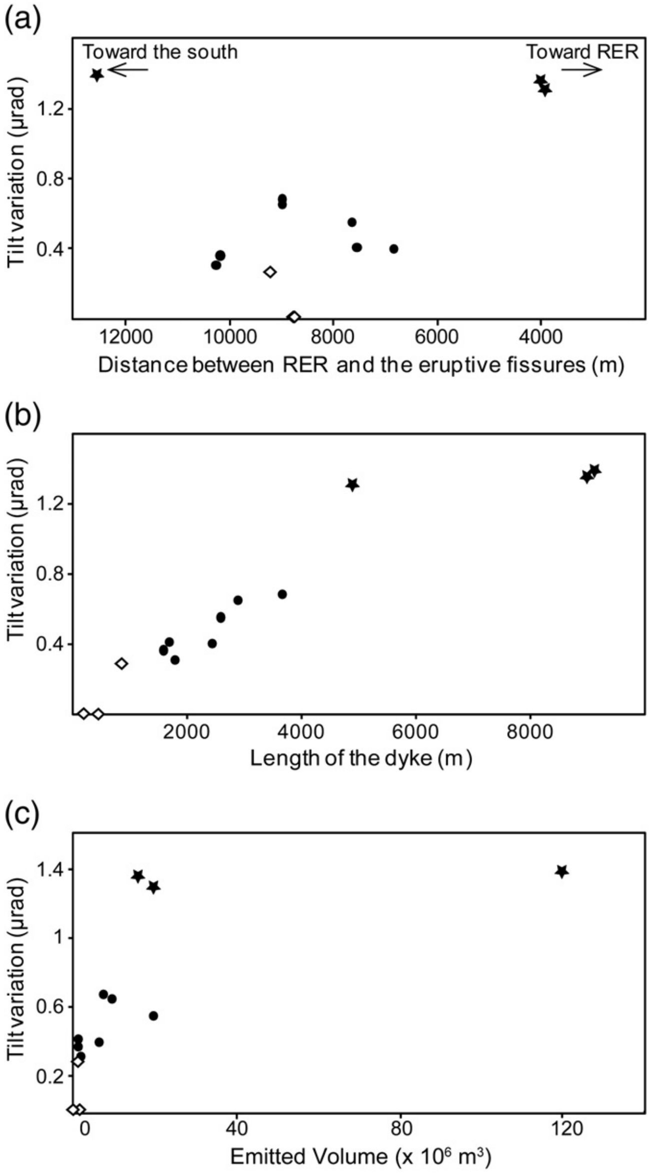

Fig. 7. Tilt variation recorded on the RER EW tiltmeter during dyke propagation versus (a) distance between the RER station and the eruptive fissures, (b) length of the dyke and (c) erupted volume. Stars, points, and diamonds represent distal, proximal and summit eruptions, respectively.

variations at RER were the largest (in terms of length and erupted volume) regardless of their location relative to RER (Fig. 7b). This suggests a preponderant role of the volume (overpressure) and/or depth of the dyke rather than dyke location on the magnitude of the RER signal, and this magnitude can be inferred from the first stages of dyke propagation below the summit. Largest and deepest dykes are associated with distal eruptions at Piton de La Fournaise (Peltier et al., 2009a).

5.1.2. Influence of the depth

The deeper the pressure source, the larger the ground deformation recorded at distant stations. The strongest tilt down to the east at RER during the first stage of dyke propagation below the summit was recorded during dyke propagations that led to distal eruptions (both on the north-eastern and south-eastern flanks; Figs. 5, 6; Table 1). This result suggests the possibility of a deeper dyke root than for dykes that fed the summit and proximal eruptions. Peltier et al. (2009a) proposed that dykes feeding summit eruptions started directly from the top of the magma reservoir and the ones feeding distal eruptions started from the eastern bottom of the magma reservoir.

The influence of a deep magma source was also recorded at RER during the Dolomieu crater collapse in 2007. On April 5 and 6, the RER station recorded cyclic tilt variations linked with the collapse. According to Michon et al. (2007b), Peltier et al. (2009b) and Staudacher et al. (2009), each cycle was characterized by a progressive inward deflation of the summit zone followed by sudden outward displacements during collapse events. On the RER station, the EW tilt signal was reversed from this pattern suggesting cycles of 30–60 min of tilt down to the east (inflation to the west) followed by a rapid tilt down to the west (0.2–2 µrad; Fig. 5c, d). The contradictory signals recorded at the summit and RER tiltmeters supports the hypothesis of a narrow and deep column of rock collapsing into the shallow magma reservoir, as suggested by seismicity (Massin et al., 2009). The 30–60 min of inward summit displacements at RER were caused by the subsidence of the rock column into the magma reservoir, which generated a deep overpressure in the reservoir; the outward summit displacements may be related to stress relaxation following each collapse event (Michon et al., 2007b; Peltier et al., 2009b). The presence of a narrow and deep rock column acting on the magma reservoir has been already suggested by Michon et al. (2007b) and Peltier et al. (2009b) to explain the increase of the lava effusion rate.

5.1.3. Influence of the volume of the dyke

Distal eruptions were fed by the largest dykes and emitted the largest volumes of lava flows (~20 Mm^3 in February and December 2005 and ~140 Mm^3 in April 2007). Such large volumes of magma associated with distal eruptions are consistent with large associated RER EW tilt signals (Table 1) as shown by the positive correlation between tilt magnitude and both dyke length and erupted volume (Fig. 7b, c). For the distal eruptions, the greater volume involved was apparent from the initiation of the dyke below the summit (Table 1, Fig. 6). By contrast, dyke propagations leading to summit eruptions (which average less than 2 Mm^3 of lava; Peltier et al., 2009a) did not create significant tilt changes at RER (Fig. 3).

In the course of the major distal eruptions of December 2005 and April 2007, the continuous tilt down to the east suggests a continuous feeding of the plumbing system throughout the eruption, in agreement with the high lava effusion rates observed at the surface (Fig. 5).

5.2. Pre-eruptive signal: detection of quick deep refilling?

Superimposed on the signal generated by the dyke propagation, a significant tilt seems to be recorded at RER two days before the June 2001 and February 2005 eruptions (Figs. 4a, 5a; ~0.7 µrad down to the west in June 2001; ~0.6 µrad down to the east in February 2005, whereas no significant signal was recorded on the summit tiltmeters. This behavior could suggest a rapid magma influx from the deep conduit to the shallow reservoir. A deep refilling generate a large extend of ground deformation and thus subtle signals that can be recorded on the RER station, whereas such signals are hidden on the summit stations. Indeed summit stations, installed directly on the ground, recorded a high background noise and daily variation reaching up to 80 µrad. The hypothesis of a deep refilling is in agreement with the Pb isotope studies (Vlastélic et al., 2007) that indicate the June 2001 and February 2005 eruptions were fed by less-contaminated, presumably deeper, magma revealing that the whole system (from the oceanic crust to the shallow reservoir) was quickly recharged by new magma just before these two eruptions. Due to the long-term background noise and the small magnitude of such a signal (Fig. 2), only a rapid refilling can be discriminated on the RER tiltmeters (Table 1). The lack of such a rapid deformation signature before other eruptions suggests slow, continuous refilling from depth, resulting in contamination of the magma by the volcanic edifice (Vlastélic et al., 2007).

Previous studies, based on the tilt derived from the GEOSCOPE VBB seismic station for the 1991, 1992, 1999 and 2000 proximal eruptions, indicated at the beginning of the dyke propagation a minor tilt down to the south–west (less than 0.04 µrad) preceding the tilt down to the north–east (Battaglia et al., 2000). These authors explain the tilt reversal as a consequence of shallow magma drainage below the summit. In case of no tilt reversal, as they observed in 1998, Battaglia et al. (2000) suggested the influence of new magma supply from deeper sources. The lack of similar tilt reversal since 2001 agrees with continuous deep refilling of the shallow magma reservoir between 2000 and 2007, as suggested by Vlastélic et al. (2007) and Peltier et al. (2008, 2009a).

5.3. Early warning and detection of eruption type

We saw in the previous sections that the largest distal eruptions generated the largest amplitudes of the RER tilt signal during the first stage of the vertical dyke propagation below the summit craters (Table 1). So regarding the amplitude of the signal recorded at RER during this first stage of dyke propagation, we propose a threshold value of 0.5 µrad of EW tilt above which a distal eruption is expected. This threshold value is reached on the EW tiltmeter when the dyke is still below the Dolomieu crater (Table 1), i.e. a few minutes/hours before the beginning of the eruption, early enough to provide warning to populations on the volcano's flanks. The RER tiltmeter station is therefore an important complementary tool to the summit ground deformation network: the summit network allows for detection of dyke propagation towards the flank, while the RER station allows for evaluation of the expected eruption type.

For volcano monitoring, installation of high precision distant tiltmeters along the lower slopes of a volcano where distal eruptions threatening population could occurred, as Etna or Karthala volcanoes, may provide warnings of large eruptions with enough lead time to allow for short-term hazards mitigation efforts.

6. Conclusion

The distally-located RER tilt station gives important information on the early propagation of dykes from the summit to the lower flanks of the volcano. The RER tiltmeters provide information on the extent of deformation and appear to be powerful tools for forecasting the type of eruptions during the first stage of dyke propagation (i.e., few minutes–hours before the beginning of the eruption). In the future, this information should contribute to the early detection of large eruptions at Piton de La Fournaise. The distant RER station is a complementary tool to the less sensitive summit stations, where such subtle signals are hidden by high tilts generated by magma transport below the summit. In terms of a monitoring strategy in volcanic areas, implementation of distant tiltmeters along the lower slopes of a volcano should contribute to better forecasts of large eruptions early enough to give warning to populations located on the volcano's flanks. Contrary to GPS, which can be disturbed by tropospheric effects and other cm-scale errors, distant tiltmeters well isolated from outside temperature variations, can be robust enough to record subtle precursory signals prior to large distal eruptions.

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