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Subtle precursors of volcanic eruptions at Piton de la Fournaise detected by extensometers

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[1] The highly active Piton de la Fournaise volcano is an excellent field laboratory to develop and test, in a short time span, new methods for detecting volcanic precursors. Since 1995, a network of four extensometers has been installed and has detected extensional, shear and vertical movements of fractures in relation to ground deformations of the volcano. This study describes new insights in the distribution of stresses in the volcanic edifice between eruptions and during magma intrusions. Continuous measurements show that all eruptions were preceded several months before by significant fracture movements: a constant opening associated with a dextral movement on the south flank and a sinistral movement on the north flank of the volcano. These movements can be attributed to a shallow pressure source below the summit craters. **Citation:** Peltier, A., T. Staudacher, P. Catherine, L.-P. Ricard, P. Kowalski, and P. Bachèlery (2006), Subtle precursors of volcanic eruptions at Piton de la Fournaise detected by extensometers, *Geophys. Res. Lett.*, 33, L06315, doi:10.1029/2005GL025495.

1. Introduction

[2] Frequently active volcanoes are ideal places to define the most suitable instrumental monitoring systems. Regarding the prediction of an eruption, the classical tools such as seismology and the measurement of surface deformations have proven their usefulness to investigate magmatic processes [Dzurisin, 2003]. However, techniques like global positioning system (GPS), electronic distance measurements (EDM), triangulation or precise levelling providing high spatial resolution data require networks with a large number of benchmarks, more or less accessible, to cover a specific area of interest. Logistical as well as financial considerations prevent geodetic networks being reoccupied often enough to reveal short-term changes. A very good useful supplement to monitor ground deformation is obtained by continuous, real-time monitoring techniques: tiltmeters, distancemeters or GPS, requiring a high level of technical and financial support. Further approaches to detect new precursors of eruptions are thus useful.

[3] Piton de la Fournaise (PdF) volcano is considered as an excellent natural laboratory because of its high frequency of eruptions allowing to develop and test in a

short time span new tools to detect alternative volcanic precursors.

[4] Internal variations of pressure related to magmatic processes induce variations in the crustal stress distribution causing deformations of the volcanic edifice. Near the free surface, these deformations can be recorded by displacements across open fractures [Gudmundsson and Loetveit, 2005]. Such structures are ideal sites to detect subtle displacements revealing the first weak variations of stress redistribution at depth.

[5] At PdF, volcanic activity is mainly expressed by fissure eruptions taking place along two rift zones (N10°E and N170°E) and a broad eruption axis oriented N120°E (Figure 1). The installation of extensometers across open fractures at these rift zones allow to measure subtle changes in the deformation field, and therefore better understand how magma is injected into the PdF flanks, and impacts on the stress field at the surface. Systematic observations carried out during 7 years and 14 eruptions, between 1997 and 2003, show their ability to measure very small changes across the fractures up to several months before eruptions, and make extensometers one of the most powerful tools for long-term forecasts of eruptions.

2. Extensometers Networks at Piton de la Fournaise

[6] Four stations have been installed by the Piton de la Fournaise Volcanological Observatory along the main North-South axis of eruptive activity on 3 to 5 cm-sized fractures (Figure 1). Two instruments, at “La Soufrière” (SOUF) and “Dolomieu Sud” (DOLO), are located near the Dolomieu crater rim and another two are located at the base of the summit cone about 2 km away from Dolomieu crater on the North at “Magne” (MAGNE) and on the South at “Château Fort” (CHAF) (Figure 1). At all sites, we used fractures, tenths of meters long, in large slabs of massif rock. Fractures at SOUF, MAGNE and CHAF have a global North South extension, whereas the fracture at DOLO is oriented East West. Each station is equipped with three individual extensometers measuring the relative displacements perpendicular to the fracture (extensional component), parallel to the fracture (shear component) and the relative vertical movement of one side of the fracture to the other (vertical component). Displacements are measured every minute. In order to reduce thermal effects, extensometers were mounted on 2-cm long silicon rods and each station is protected from exposure to sun light by an insulating foil and a plastic box. Technical improvements allowed us to reduce the temperature dependent

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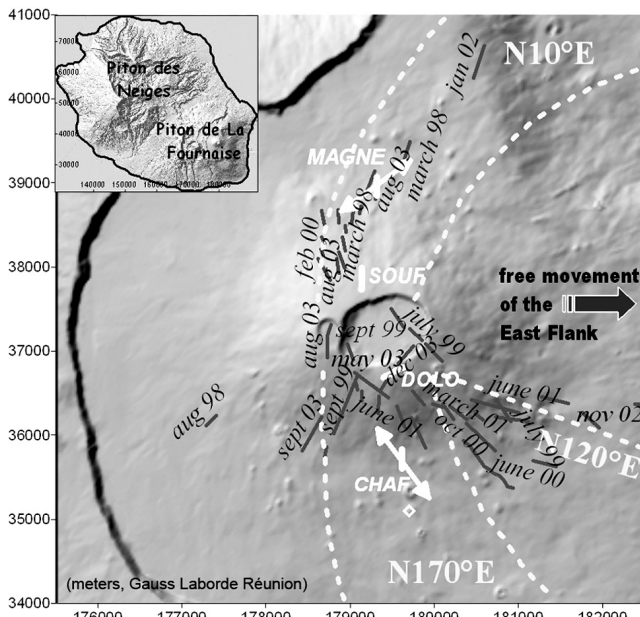


Figure 1. Structural map of Piton de la Fournaise. The rift zones are limited by dashed white lines. The solid white lines, black lines, and diamonds indicate respectively the location of the extensometers, the eruptive fissures from 1998 to 2003, and the CHAF tiltmeter station.

daily variations up to 0.005mm (Figure 2) (see auxiliary material¹).

3. Data From 1997 to 2003

[7] In this study, we focus on data acquired by the CHAF and MAGNE extensometer located at the base of the summit cone which cover the evolution over 7 years without any interruption. The data show a constant opening of these fractures during 7 years, superimposed by strong, short-term movements (opening or closing) (Figure 3). At PdF, these rapid ground displacements in terms of a few hours are always caused by high-speed rising of magma prior to the onset of an eruption [Lénat and Bachélery, 1990; Peltier et al., 2005]. Recorded movements before and during each eruption are reported in Table 1.

3.1. Long Term Behaviour

3.1.1. CHAF Extensometer

[8] The general evolution of the vertical component over 7 years shows only small variations on a long time scale as well as before and during eruptions (Figures 3a and 3b). On average, and without considering intrusive events, the value decreases by about 0.35 mm over the first 3 1/2 years, corresponding to the relative subsidence of the East rim of the fracture (Figure 3b). Since 2000, this trend is reversed with a relative uplift of 0.23 mm between 2000 and 2003 of the East side of the fracture (Figure 3b). The shear component shows larger variations during magma intrusions but also between eruptions, shifting by about 0.9 mm since 2000 corresponding to a dextral displacement (Figure 3b).

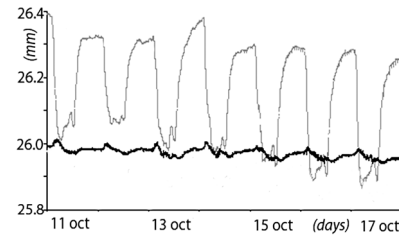


Figure 2. Extensometer variations recorded in 1999 during a quiet period. Grey values represent the raw data; black values are corrected.

[9] The extensional component shows the largest systematic variations with a constant rate at long term considering the movement without eruption (Figure 3b). Since mid-1999, the signal reveals an accentuation of the extension, with a rate of 0.6 mm/year, matching with the increase of the eruptive activity.

3.1.2. MAGNE Extensometer

[10] The general tendency at long term is the same as for CHAF, with a constant opening since mid-1999 at a rate of about 1 mm/year, a relative uplift of the East edge of the fracture, accompanied on the North flank with a sinistral shear displacement (Figures 3c and 3d and Table 1).

3.1.3. Comparison Between Extensometric and Tiltmeter Variations

[11] In Figure 4, we compare the extensometer and the radial tilt variations at CHAF before each eruption. Electronic tilt monitoring, with highly sensitive sensors for short period measurements, is one of the most suitable tools to monitor subsurface magma movement during dyke propagation. In contrast, slower deformations, caused by pressure changes at depths, during days or months before an eruption appear to be more difficult to record and analyse, due to the perturbation caused by meteorological fluctuations and long-term instrumental drift.

[12] Just before most of the eruptions, a good correlation could be obtained between tiltmeter data showing summit

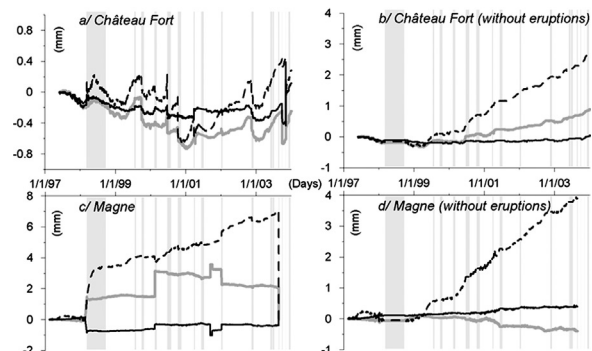


Figure 3. (a, c) Extensometer displacements recorded during 1997 to 2003 on the opening (black indents), shear (grey lines) and vertical (black lines) components. An increase of the values corresponds to an opening, a dextral movement or an uplift of the East side of the fracture, respectively. Grey areas represent periods of eruptions. (b, d) Same displacements as above without the short-term ground deformations due to dyke injections.

¹Auxiliary material is available at <ftp://ftp.agu.org/apend/g/2005gl025495>.

Table 1. Displacements on the Two Basal Extensometers Before and During Dyke Injection Prior the Eruptions of 1998 to 2003^a

Date	Magne			Chaf			Chaf Behaviour During Eruption	
	Total Opening, mm	Considered Period, days	Opening Rate, mm/day	Total Opening, mm	Considered Period, days	Opening Rate, mm/day	Opening, mm	Shearing, mm
9 Mar 1998	-0.13	80	-0.0016	0.05	30	0.002	0.31	0.08
19 Jul 1999	0.465	100	0.0047	0.31	100	0.003	0.11	0.1
28 Sep 1999	0.054	50	0.0011	0.045	55	0.001	-0.04	-0.02
14 Feb 2000	0.04	100	0.0004	0.16	88	0.002	0.08, -0.08	0.06
23 Jun 2000	0.59	100	0.0059	0.33	40	0.0083	-0.5	-0.3
12 Oct 2000	0.274	100	0.0027	0.25	80	0.003	-0.31	-0.05
27 Mar 2001	0.354	77	0.0046	0.3	83	0.004	-0.03, 0.03, -0.08	0.1
11 Jun 2001	0.35	70	0.0050	-0.106	40	-0.003	-0.04, 0.04	?
05 Jan 2002	0.32	130	0.0023	0.3	130	0.002	0.027, -0.024	0.036
16 Nov 2002	0.358	100	0.0036	0.31	100	0.003	-0.07	-0.134
30 May 2003	-	-	-	0.22	71	0.003	-	-
22 Aug 2003	0.56	122	0.0046	0.483	122	0.004	0.1	0.08
30 Sep 2003	-	-	-	0.13	30	0.004	0.23, -0.27	0.11, -0.5
07 Dec 2003	-	-	-	0.18	26	0.007	-	-

^aA positive value corresponds to an opening and a dextral fracture movement, respectively.

inflation and the opening of the CHAF fracture. The signal on the extensometer is much clearer due to its weaker dependence on meteorological effects. Prior to the June 2000 and 2001, May and September 2003 eruptions, the tiltmeter network did not record any significant change while the extensometer network shows an increase of the fracture opening up to three months before the eruption, demonstrating the high ability of such a network to forecast eruptions.

[13] Contrary to tiltmeters and GPS data, extensometers cannot be easily used to constrain the pressure source location, but their continuous recording allows determining the chronological evolution of the stress field in the rift zones while a dyke propagates.

3.2. Short Term Behaviour

[14] Magma injections act strongly on the pre-existent fractures but their influence varies as a function of the position of the eruptive fissures (Figures 3a and 3c and Table 1). For eruptions taking place on the northern flank, as in Mars 1998 or January 2002, the CHAF fracture remains open during the first days of eruption, whereas it closes immediately for the South flank eruptions. The shear movement of the fractures is also distinct (Figures 3a and 3c and Table 1). When a dyke opens at the East of the CHAF extensometer, as in June 2001 or November 2002, the fracture accommodates deformation with a dextral shear

movement, and with a sinistral shearing when the dyke opens at the West.

3.3. The September 2003 Eruption

[15] During the dyke injection preceding the September 2003 fissure eruption (located on the South flank, at 1200 meters at the West of the CHAF extensometer), the fracture opened by 0.29mm and closed just before the eruption started (Figure 5). In order to study the effect of dyke position on the extensometer response we model the movements of the CHAF fracture, during this dyke intrusion. We employ a three-dimensional elastic, homogeneous and isotropic half space model based on the mixed boundary element method developed by *Cayol and Cornet* [1997]. The method takes into account the topography and the shape of active dykes and passive fractures, and allows to calculate displacements associated with an intrusion at each point of the surface as well as at each point of the fractures. According to field observations and previous models, we consider the CHAF fracture as not very extended at depth and represent it by a size of 30 × 20 meters. A larger fracture would show larger displacements incompatible with the observations. We used the shape of the dyke modelled by *Peltier et al.* [2006] and driven by a constant overpressure of 1.5 MPa. Contrary to Krafla fires 1975–1984 [*Gudmundsson*, 1995], at PdF lateral dykes emplaced in one eruption, and propagated in two stages: a first vertical migration under the Dolomieu crater followed by a lateral migration to the flank (Figure 6) [*Peltier et al.*, 2005, 2006]. The dyke grows toward the surface and the flank by increasing its height and length.

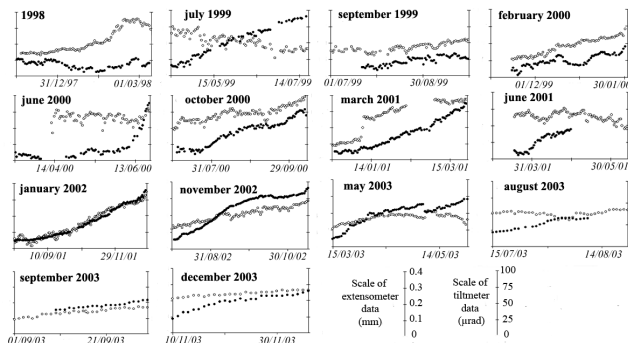


Figure 4. Comparison between extensometer opening (solid circles) and tiltmeter variation (open circles) at CHAF station before eruptions of 1998 to 2003.

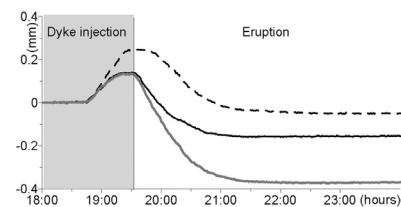


Figure 5. CHAF extensometer displacements during the dyke injection and the beginning of the September 2003 eruption recorded on the vertical (black lines), opening (black indents) and shear (grey lines) components.

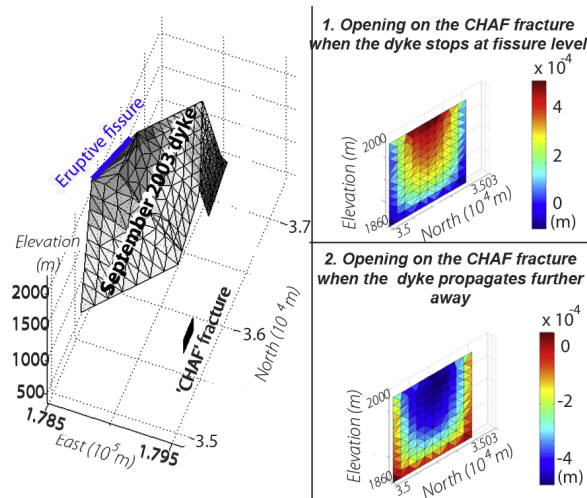


Figure 6. Displacements modelled on the CHAF fracture during the September 2003 dyke injection.

During vertical migration and until the migrating dyke arrives below the eruptive fissure, the model indicates an opening and a sinistral shear movements of the CHAF fracture, in agreement with a stress generated by the emplacement of the dyke West of the structure (Figure 6). As soon as the dyke reaches the surface and propagates beyond the vents in direction of CHAF, the fracture closes. This closing occurs after the beginning of most of the eruptions on the southern flank, and continues for several days or weeks.

4. Discussion

[16] The relative movements across two fractures, reflecting the stress distribution of the rift zone, allow us to determine and extrapolate on a larger scale the behaviour of the rift zone before and during eruption. Most of the eruptions at PdF are preceded by precursors generally corresponding to an increase of shallow seismicity located above sea level, correlated with weak summit inflation. As soon as the internal pressure increases in the magma chamber, stresses are generated on surrounding rocks resulting in ground deformation. This stress change influences the pre-existing fractures which accommodate deformations with a detectable reopening (Figure 4). One to three months prior the 14 eruptions, occurring during the period 1997–2003, a systematic opening of the fractures was observed. In most of the cases, the eruption started when the opening component at CHAF reached a value of about 0.3 mm (Table 1). This value appears to represent a limit at which the upper structure of the volcano fails. This implies that the same internal structure of the volcano undergoes an overpressure and remains almost the same from one eruption to the next. According to seismicity and data from other deformation networks, this source of overpressure is located in a shallow magma chamber below the summit craters [Peltier *et al.*, 2006]. The CHAF and MAGNE extensometers, which are located approximately at the same distance from the summit, show different opening values, probably due to different sizes of the fractures. A deeper and longer fracture amplifies the surface deformation more.

[17] The constant and long-term opening, accompanied by shear movements (dextral at MAGNE and sinistral at CHAF) is in agreement with the general tendency of a displacement of the PdF eastern flank toward the sea (Figures 1 and 3). The repeated dyke injections along the rift zones affect the East flank by reducing its gravitational stability. When an overpressure occurs at shallow depth below the summit, rift zones are activated and tend to push the East flank toward the sea with a dextral movement in the North and sinistral in the South.

[18] This continuous shift shown by the two extensometers between eruptions is overprinted by strong variations due to dyke intrusions. In contrast to long term movements, short and strong movements differ from one eruption to the other as a function of the position of the eruptive fissure. When eruptions occur on the South flank and close to CHAF, as in September 2003, the pre-existing fractures are reactivated by the local stresses of the nearby dykes (Figure 6). The dyke migrating toward the surface changes the stress field around pre-existing fractures, inducing tensile stress concentrations at the upper tips of the boundary faults that tend to open this superficial structure [Gudmundsson and Loetveit, 2005]. The faults stay open until the magma front arrives at shallow level and generates stresses that close the fault and then slips as a reverse fault (when the fault is normal). This behaviour is maintained on the faults until the compressive stresses generated by the magmatic overpressure are relaxed during or after the end of the eruption, when magma pressure decreases or ceases completely. The North flank eruption, far from the CHAF fracture, does not act directly on this structure, and generates only a first dextral opening, corresponding to the accommodation of a shallow overpressure under the edifice, followed by a closing due to the relaxing of the edifice, once the eruption started. The May and December 2003 summit eruptions do not influence the behaviour of the CHAF extensometer, implying that the strong structural control of the rift zone in the lateral dyke capture is not involved in summit eruptions.

5. Conclusion

[19] Changes in the stress field under the central cone of PdF due to a shallow pressure source in the magma chamber, undergoing an overpressure or due to dyke emplacement, can be well constrained by an analysis of the continuous data set of extensometers. Subtle displacements of the open fractures in response to an pressure increase in the magma chamber makes the extensometer to be a simple, cheap and one of the most powerful and most sensitive tool to record long-term precursors of eruptions. At PdF this precursor can be identified up to three months in advance. The 7 year data on two extensometers reveal new evidence on the preferential displacements of the East Flank toward the sea. Such a situation may create in future a flank instability and cause, as happened 4500 years ago, a new catastrophic landslide of the eastern flank of PdF.

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