

Eruptive fracture location forecasts from high frequency events on Piton de la Fournaise volcano

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Piton de la Fournaise (La Réunion island) is a very active basaltic volcano, with 5 eruptions between Nov. 2009 and Dec. 2010. The pre-eruptive seismic crises only last for a few hours and mainly consist of a Volcano-tectonic swarm. During the quiescent period between the VT swarm and the eruptive tremor, we identify another swarm of events with a very high frequency content. These events are shallow and are located close to the future eruption site. They seem associated with the opening of the path for the magma propagating laterally at shallow depth. As these events start to occur while the magma is still in a vertical propagation phase, this seismicity seems to be related with the generic response of the volcano to the stress perturbation and not directly induced by the magma pressure. This new observation may bring new insights to short term forecasting of the eruption location.

1. Introduction

Piton de la Fournaise (PdF) volcano is a hot-spot shield volcano located on La Réunion island in the Indian Ocean. This very active volcano erupted more than 30 times between 2000 and 2010 [Roult *et al.*, 2012]. The eruptions are usually of short duration, lasting from a few hours to a few months and emit basaltic lava. Eruptions are either summital in the Dolomieu crater, proximal (on the flank of the central cone) or distal at more than 4 km from the summit [Peltier *et al.*, 2009]. Since the end of 2009, the volcano is monitored by 21 broadband seismic stations [UNDERVOIC project; Brenguier *et al.*, 2012], which have recorded five eruptions (5 Nov. 2009, 14 Dec. 2009, 2 Jan. 2010, 14 Oct. 2010, and 9 Dec. 2010).

The pre-eruptive seismicity on Piton de la Fournaise is characterized by a dense swarm of Volcano-Tectonic (VT) events [Battaglia *et al.*, 2005; Massin *et al.*, 2011; Brenguier *et al.*, 2012]. These events are mainly located around sea level, i.e. at about 2500 m below the summit. Several Long Period events may occur toward the end of the seismic crisis, but only for proximal and distal eruptions [Aki and Ferrazzini, 2000; Zecevic *et al.*, 2013]. These VT crises are

followed by a period of pre-eruption quiescence, with a duration of several hours, which in turn are followed by the eruptive tremor accompanying the flow of lava. This simple and repetitive sequence of events exactly follows the general pre-eruptive pattern of seismicity described by McNutt [2005].

The high resolution network of seismic stations, the frequent recurrence and the short time duration of eruptions and the simplicity of the pre-eruptive patterns make this volcano an exceptional laboratory to develop new forecasting observations [e.g. Schmid *et al.*, 2012]. We mainly focus here on the seismicity occurring before the proximal eruption of the 14th Oct. 2010. Interestingly, after the main seismic swarm of VT events, we identify a second swarm of events with an higher frequency content during the quiescence time at the stations the closest from the eruptive vents. This paper aims at investigating the origin of these events, and their potential for short-term forecasting of the location of lava extrusion.

2. The 14th October 2010 eruption

Since the end of 2009, the volcano has been monitored by 21 broadband seismic stations, including six 60-sec Guralp CMG-3ESPC sensors and fifteen 30-sec Guralp CMG-40T sensors [UNDERVOIC project Brenguier *et al.*, 2012]. All data used in this paper have been corrected for instrument response. The station distribution is exceptionally good with stations on the ridge of the main crater and an average distance of 1 to 2 km between stations.

Figure 1 shows the seismic crisis recorded by two stations (U05 near the summit and FOR in the South, see fig.2c). The main swarm of VT events started at 10:00 and lasted for less than 2 hours, after which a quiescence period of 3 hours commenced. At 15:20, lava started to flow from a 150 m long fissure which opened South of the Dolomieu crater in the “Enclos Fouquet” [see fig.2c and Roult *et al.*, 2012]. The activity decreased after the 17th Oct., and stopped on the 31st Oct.. This eruption is the first proximal eruption since the major eruption and crater collapse of 2007.

For both stations, the seismic energy is very strong during the main VT swarm and the eruptive tremor episode. This energy is mainly present in a low frequency range (i.e. less than 10 Hz). While the quiescence period is almost free of visible events in the U05 data, a swarm of events can be seen at FOR station between 13 and 15:00. This swarm of events has a higher frequency content than the VT swarm. The energy of the signal filtered between 20 and 40 Hz clearly show these events (see fig. 1). Herein, we refer to the events forming this swarm as High Frequency (HF) events.

3. High Frequency events

Figure 3 shows a close-up of two events, one VT event recorded during the main seismic crisis and one HF event.

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They differ in their amplitudes (2 orders of magnitude), and their frequency content. The spectra of the VT and HF events show a classical earthquake pattern, with a corner frequency of 6 Hz and 14 Hz, respectively. The HF events also seem to be volcano-tectonic (i.e. with a shear, brittle mechanism), but occur on smaller faults or smaller patches of the faults.

When looking at the waveforms recorded by different stations, the HF events can be seen at only 4 stations. Due to their low amplitude, the lowest frequencies of the signals are masked by noise at all stations. The high frequency content, which is clearly visible in FOR data, is strongly scattered and attenuated, and subsequently cannot propagate very far from the source. It is therefore not possible to perform a quantitative location for these sources. In order to estimate the location qualitatively and to link the HF event with the other seismic signals, we interpolate the seismic energy onto the surface of PdF volcano [Battaglia and Aki, 2003]. This is achieved using a cubic interpolation of the total energy measured in 5-minute windows filtered in a low frequency band (0.5-5 Hz) and in a high frequency band (20-40 Hz). Three snapshots are shown in figure 2, corresponding to 1) the main VT swarm, 2) the HF swarm and 3) the eruptive tremor periods. The movie A2 (aux. mat.) shows the continuous distribution of the energy in both frequency bands along the entire pre-eruptive sequence. The VT crisis is associated with high energy at both frequency bands, located at depth below the summit. High frequency energy starts to appear South of the Dolomieu crater, and becomes progressively more visible during the quiescence period, which is dominated by the HF swarm. The eruptive tremor mainly contains low frequencies, and also occurs in the South of the volcano around the eruptive vent. Unlike the VT seismicity, the HF events yield information on the future eruptive fracture location (see fig. 2) as their energy strongly decay with the offset from this area, where their epicenter seems to be located. Moreover, a deep source (i.e. at a depth greater than the inter-station distance) would produce similar amplitudes on different stations. Hence, the sources of these events have to be shallow. This is supported by the b-value in the Gutenberg-Richter law: a value of 0.9 and 1.55 is obtained for the VT swarm and HF swarm, respectively. This high value is a distinctive feature of events occurring in a low stress environment [Schorlemmer et al., 2005], such as in the shallow sub-surface of the volcano.

4. Pre-eruptive behavior

The HF swarm mainly differs from the VT swarm through its higher frequency content. Therefore, the ratio between the high frequency and the low frequency contents can be used to indicate the presence of HF events. Figure 4b shows the cumulative ratio for all stations, computed on 5 minute long windows. As expected, this ratio is the highest in the stations for which high frequency events can be seen, and which surround the eruptive fracture. For those stations, this ratio starts to increase significantly at 10:00, i.e. before the main VT crisis and more than 5 hours before the eruption onset. For the other eruptions in 2010 and 2011, the highest ratio is always observed at the stations that are the closest to the area where the eruption will occur a few hours later (see movie A2). This method can therefore be performed to forecast the location of the impending eruption.

The average depth of the seismicity is derived with the seismic intensity ratio method described by Taisne et al. [2011]. In order to use waves propagating through all the

network and to consider the different types of events, we focus on the 5-15 Hz frequency band. We assume a S-wave velocity of 2 km/s [consistent with *Brenquier et al.*, 2007]. The seismicity first has deep and scattered source locations (around sea level), and then migrates toward the surface between 11 and 12:00, i.e. at the end of the VT crisis (fig. 4c). As usually observed on PdF [Peltier et al., 2009], the GPS data indicate a two phase deformation, and GPS stations close to UV5 and FOR (fig. 2c) show different deformation patterns (fig. 4d). The dike first propagates vertically, leading to high deformation of the volcano summit between 10:55 and 12:00. From 11:30, the magma starts its lateral propagation toward the South, the deformation is localized only in the South of volcano after 13:00.

The different observations summarized in fig. 4 show that: 1) the VT swarm occurred at the beginning of the vertical propagation of the magma. The vertical migration of the seismicity is associated with deformation localized on the summit; 2) During the lateral propagation of the dike, deformation and seismicity (HF events) are only recorded in the South of the volcano; 3) the HF/LF ratio starts to increase in the South of the volcano toward the end of the VT swarm, i.e. when the dike is still in its vertical migration phase.

5. Discussion and Conclusion

During the quiescence period occurring between the main seismic crisis and the eruption, we observe a second swarm of high frequency events at some stations. This observation is rendered possible thanks to the highly dense seismic network deployed on the volcano. These events seem to be generated at very shallow depths compared to the classical VT events, which usually occur at depths greater than 1 km [Battaglia et al., 2005; Massin et al., 2011]. Using energy mapping, we determine that the HF events are located in the area of the eruptive fracture. As they have a high frequency content which is lacking in the VT events, high-to-low frequency ratios allow us to track their evolution. Their high frequency contents indicate failure on small faults (or small patches), with a diameter no greater than 60 m [Madariaga, 1976]. This is consistent with a shallow seismicity, as the near-surface cannot support large faults because of the topography and/or weak material properties. Therefore, the VT and HF in this study share a similar mechanism, and belong to the same group of events.

These HF events may have significant implications for monitoring purposes: monitoring the high-to-low frequency energy ratio during the main seismic crisis (i.e. a few hours before the eruption onset) allows for a forecast of the eruption location. This is confirmed here by computing this ratio for another proximal eruption (Dec. 2010) and for summit eruptions (Nov. 2009 and Jan. 2010, see aux. mat. fig. A1). In every case, the largest frequency ratio before the eruption onset is obtained at the stations closest to the upcoming eruptions. This information can be coupled with the occurrence of Long Period events, which is an indication of an eruption outside of the summit area on PdF [Aki and Ferrazzini, 2000; Zecevic et al., 2013].

The VT and HF swarms are related to the vertical and lateral migration of the magma, respectively. However, the HF seismicity seems to start to occur during the VT swarm, i.e. when the magma is still in its vertically migrating phase

at depth (c. 2 km b.s.l.) beneath the summit. The HF seismicity is therefore likely a generic response of the shallow part of the edifice to the stress changes due to the dike propagation [Traversa *et al.*, 2010]. These failures are triggered indirectly by the stress induced by the magma movement, and not by the magma itself. As these shallow failures occur in the area of the eruption, they play a role in the process of dike propagation by creating the pathway along which the magma later propagates. The eruptive fissure might be exploiting a structural weakness which can be monitored through HF events. The shallow magma path, and the eruption area, is therefore already defined when the magma is still in its vertically migrating phase. Hence the location of lava output can be forecast up to three hours prior to the eruption.

On Piton de la Fournaise, the pre-eruptive seismicity has a short time duration and is rather simple compared to other volcanoes. However, it follows the generic swarm pattern of McNutt [2005]. The observations made herein might therefore be reproduced on other volcanoes where the station distribution is sufficiently dense.

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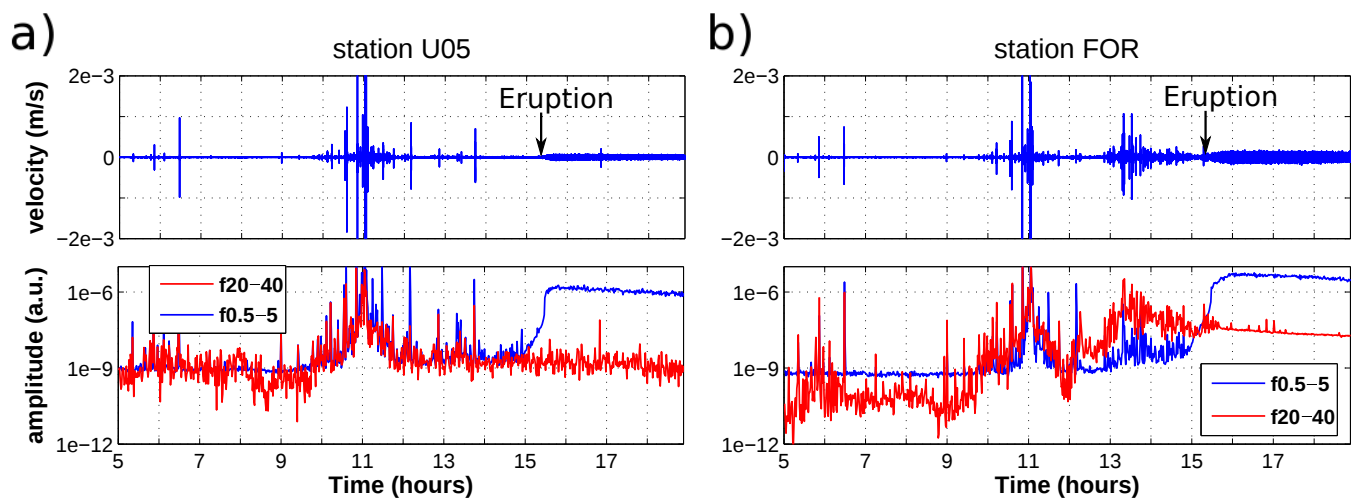


Figure 1. Vertical component of the pre-eruptive and initial eruption seismicity recorded on the 14th, Oct. 2010 by stations a) U05 and b) FOR. The lower panels show the seismic energy in 2 frequency bands (0.5-5 Hz and 20-40 Hz) for both stations. The vertical arrows show the beginning of the eruption.

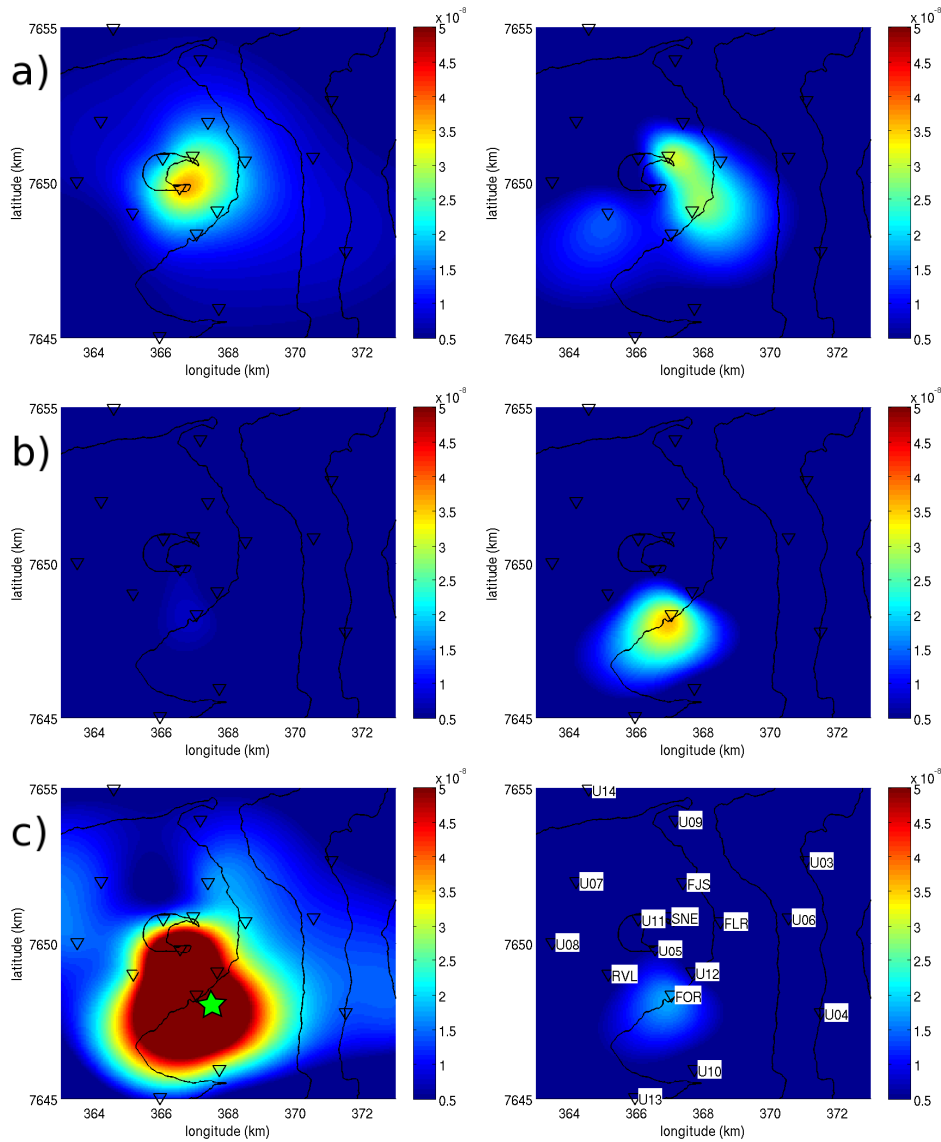


Figure 2. 5 minutes root mean square amplitude interpolated between stations on the surface of the volcano in a low frequency band (0.5-5 Hz, left panels) and high frequency band (20-40 Hz, right panel) at 3 different periods: a) Main seismic swarm (10:55), b) high-frequency event swarm (13:49) and c) beginning of the eruptive tremor (15:36). Elevation between contour lines is 500 m. Triangles show the stations and the star indicate the eruptive vent location. Color scale (root mean square amplitude) is common for all the panels. See also the movie in the supplementary material.

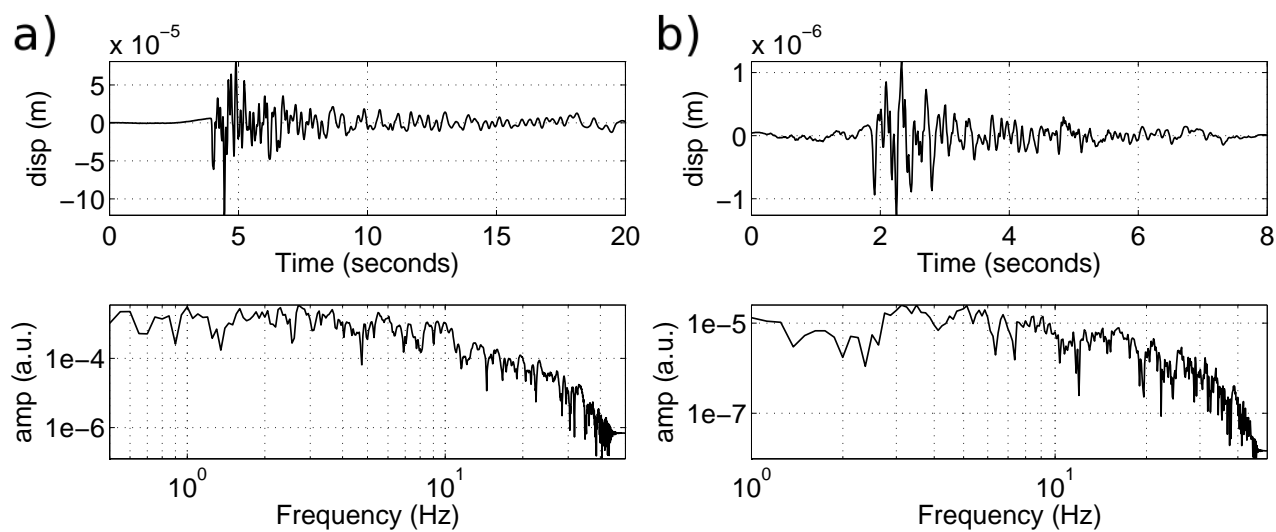


Figure 3. Seismic waveforms and spectra of a) a VT event recorded during the main seismic crisis (11:02) and b) a High frequency event (14:32). Both events are recorded at FOR station.

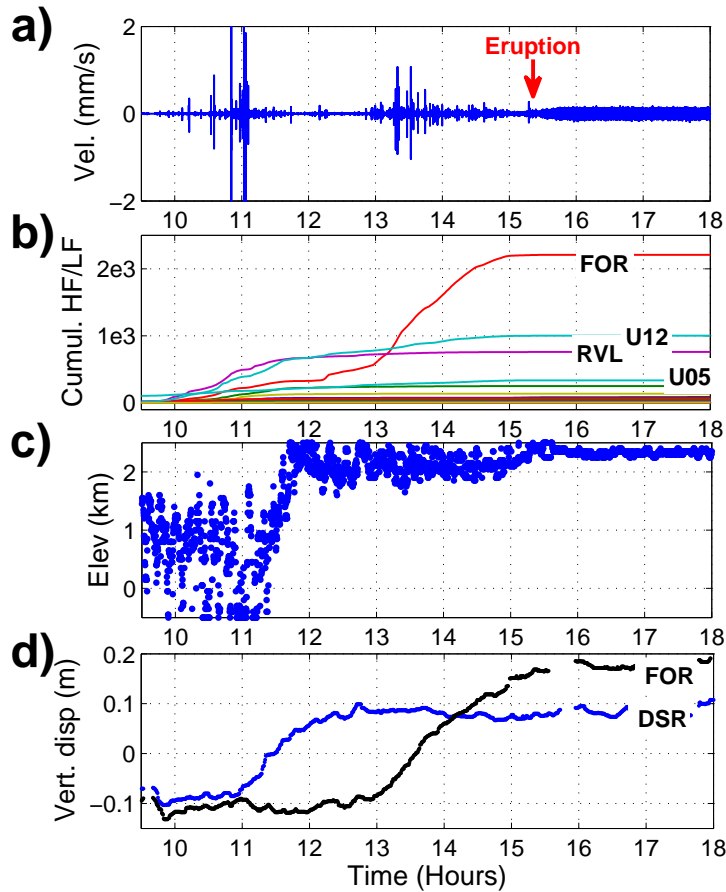


Figure 4. a) Seismic activity before and during the beginning of the eruption on the 14th Oct. 2010 recorded by the FOR station. b) Cumulative High Frequency (20-40Hz)/Low Frequency (0.5-5 Hz) ratio for all stations. The 4 highest ratios are labeled with the corresponding station names. c) Elevation of the seismicity sources using radiated seismic intensity. d) Vertical deformation recorded by the GPS station DSR (close to U05) and FOR.