April 2007 collapse of Piton de la Fournaise: A new example of caldera formation

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April 2007 collapse of Piton de la Fournaise: A new example of caldera formation

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[1] Collapse calderas are frequent in the evolution of volcanic systems, but very few have formed during historical times. Piton de la Fournaise is one of the world's most active basaltic shield volcanoes. The caldera collapse, which occurred during the April 2007 lateral eruption is one of the few large documented collapse events on this volcano. It helps to understand the mode and origin of caldera collapses in basaltic volcanoes. Field observations, GPS and seismic data show that the collapse occurred at an early stage of the eruption. The cyclic seismic signal suggests a step by step collapse that directly influenced the lateral eruption rate. Likely, the caldera results from the combined effect of (i) the progressive collapse of the plumbing system above the magma chamber since 2000, and (ii) the large amount of magma withdrawal during the early stage of the eruption by both a significant intrusion within the edifice and an important emission rate.
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1. Introduction

[2] Caldera collapse structures are common on basaltic to silicic volcanoes [e.g., *Cole et al.*, 2005]. In basaltic setting, they are defined either as pit crater or caldera. Pit craters, which correspond to small structures, tens to hundreds of meters across, may have several origins. They form along the rift zones by stopping over an underlying large-aperture rift zone fracture [*Okubo and Martel*, 1998], and at the volcano's summit by magma withdrawal in shallow reservoirs [*Hirn et al.*, 1991; *Rymer et al.*, 1998; *Longpré et al.*, 2007]. Basaltic calderas are kilometric structures usually formed during large lateral eruptions or intrusions, which affect the main magma chamber [*MacDonald*, 1965; *MacPhie et al.*, 1990; *Kumagai et al.*, 2001; *Kaneko et al.*, 2005]. Two of the most recent caldera collapses on basaltic or intermediate volcanoes occurred in 1968 in Fernandina Island, Western Galapagos [*Simkin and Howard*, 1970], and in 2000 at Miyakejima volcano [*Geshi et al.*, 2002]. In both cases, caldera collapse was interpreted as the result of large lateral magma intrusions within the edifice or the underlying crust.

[3] At Piton de la Fournaise (PdF), the volcano's summit zone experienced several coalescent pit craters during the last centuries [*Carter et al.*, 2007]. The April 2007 eruption led to the largest collapse of the summit zone and the most recent example in basaltic setting. It developed contemporaneously to one of the largest historical lateral eruptions on Reunion, suggesting a very close link between magma withdrawal and the summit collapse. This study summarizes the April 2007 eruption in order to explain the origin, the timing and the effects of the collapse. It brings new constrains on (1) the relationship between magma withdrawal and the collapse and (2) the timing of the collapse regarding recent recurrent eruptions.

2. Geological Setting of Piton de la Fournaise

2.1. General View

[4] PdF is the active volcano of La Réunion Island (Figure 1). The eruptive centre is located in a large 8 km across caldera, the Enclos Fouqué, where most of the eruptions occur since 4.5 ky [*Bachèlery*, 1981]. The present day summit shows two collapsed structures named the "Bory crater", which is currently inactive, and the "Dolomieu crater", which is the locus of numerous summit eruptions. *Carter et al.* [2007] recently showed that the pre-2007 elongated geometry of Dolomieu results from recurrent pit crater collapses.

[5] The activity of PdF is characterized by fissure eruptions fed by a magma reservoir located at about sea level [*Fukushima et al.*, 2005; *Peltier et al.*, 2007]. Considering the location of the eruption site, three types of eruptions can be distinguished. 1- Summit eruptions start and remain in Dolomieu. 2- Proximal eruptions, which may start in the summit but progress to the flanks of the central cone and usually propagate downslope to the Enclos caldera floor. 3- Distal eruptions develop away from the central cone, starting in the Enclos caldera floor. During the last century, the distal eruptions were in some cases associated with the development of summit collapses [*Bachèlery*, 1981; *Carter et al.*, 2007]. Among them, the most voluminous eruption of 1931 with 130 Mm^3 was related to a large collapse corresponding to the eastern half of Dolomieu [*Lacroix*, 1938, Figure 1]. The lack of any continuous observation and monitoring during the largest events does not allow the determination of the precise relationship between these eruptions and the associated summit collapses.

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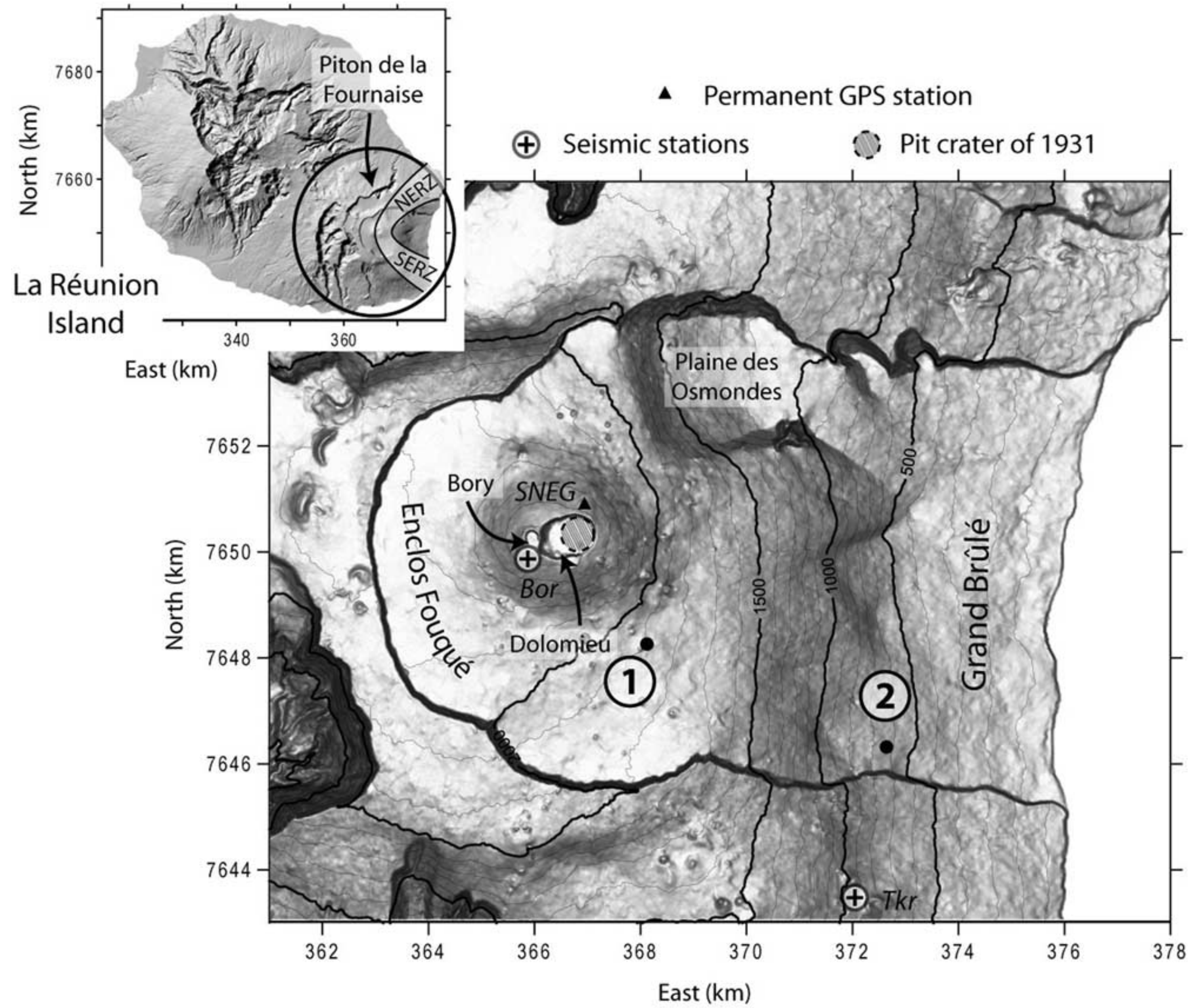

Figure 1. Location of Piton de la Fournaise volcano. The central cone is cut by two collapsed craters, Bory and Dolomieu. 1 and 2 represent the location of eruptive fissures during the first and second eruptive phases, respectively. Bor and Tkr correspond to the seismic stations used in Figure 3. NERZ and SERZ: NE and SE rift zones.

2.2. Summary of the March 1998–February 2007 Evolution

[6] Since 1998, PdF has been characterized by an intense eruptive activity with 2–4 eruptions per year. Most of the eruptions correspond to summit and proximal events. Some of them, the summit eruptions, contributed to the progressive filling of Dolomieu by the accumulation of pahoehoe lava flows. Total filling of Dolomieu was attained with the August 2006–January 2007 summit eruption during which a pile of 20–30 m of lava flows accumulated on the crater floor. Five distal eruptions occurred during the 1998–2007 period. They were mainly concentrated in the Plaine des Osmondes depression, along the NE rift zones (Figure 1).

[7] Before 2000, the eruptions of PdF were showing a similar evolution with a progressive disappearance of the tremor [*Battaglia et al.*, 2005]. Volcano-tectonic (VT) events seldom occurred during the eruptive phases (Figure 2). The eruption evolution progressively changed with an increase of both tremor amplitude and seismicity before a rapid end of the eruption [*Longpré et al.*, 2007]. Since 2000, the seismicity was especially abundant during voluminous eruptions, most of them being distal. During the November 2002 eruption, the seismicity intensified 5 days before the end of the eruption and continued at shallower levels before the collapse of a small pit crater on December 23 in Dolomieu [*Longpré et al.*, 2007]. Such a surface phenomena did not occur during the other distal eruptions despite a strong increase of the VT seismicity in both frequency and magnitude below the summit. However, the coeval intensification of the emission rate and the VT events

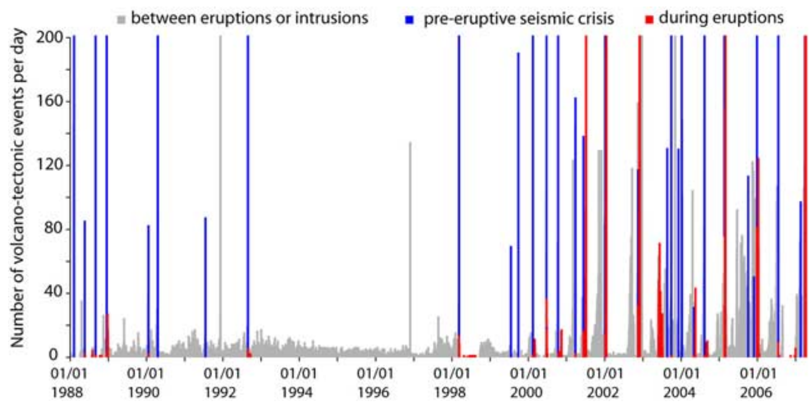

Figure 2. Volcano-tectonic seismicity between 1988 and March 2007. Note the onset of the co-eruptive seismicity since 2000.

suggests that the overlying rock column beneath Dolomieu experienced recurrent destabilizations.

3. April 2007 Eruption

3.1. Development of the Eruption

[8] On February 26 the seismic activity began below the summit zone. It progressively increased and reached the value of more than 100 daily events on March 28 to 30. A seismic crisis started on March 30 at 16:25 UTM and the magma emission begun at 18:50 from an eruptive fissure located at 1900 m asl SE of the central cone (Figure 1). The tremor ceased on March 31 at 05:15, after a first eruptive phase of less than 10 hours during which only a small volume of magma was emitted. The summit seismicity continued until the April 2 new eruptive phase in the Grand Brûlé at ~600 m above sea level and 7 km away from the summit (Figures 1 and 3). The eruption site was characterized by ~50 m high continuous lava fountains feeding voluminous lava flows. After a classical period of decreasing activity, the number of VT events gradually increased from April 3 (period 1 in Figure 3). On April 5, the VT events disappeared while both a general low frequency seismic signal and the tremor intensified (period 2 in Figure 3). The permanent GPS located ~200 m north of the northwestern rim (see Figure 1 for location) started to show an inward displacement of the summit zone at ~12:00 (Figure 3e), which was coeval with the increase of the seismic signal at the eruption site. The activity changed at 20:48 after a M_d 3.2 earthquake occurred below the summit crater (C_1 in Figures 3c and 3e). This event was contemporaneous with a sudden outward displacement of ~15 cm of the GPS station (Figure 3e). An increase of the seismic signal of ~50% was recorded at Tkr seismic station after the large earthquake. Then, the seismic signal was organized in cycles, the frequency of which gradually increased from one cycle every two hours to one cycle every 30 minutes (period 3 in Figure 3b). The seismic cycles were coeval with a step-by-step increase of the tremor until April 06 08:00 (Figure 3d). GPS data indicate that each cycle was characterized by progressive inward displacements and ended by a sharp outward motion. April 6 corresponds to a paroxysmal phase during which 200 m high lava fountains were observed in the Grand Brûlé. The first observations of the summit zone made the afternoon of the 6th revealed that the intensification of both the seismicity and the tremor was coeval with a collapse of Dolomieu (Figure 4b). The tremor progressively went down to its initial level, i.e., before the paroxysmal phase, whereas the cyclic seismic signal remained until the 7th of April 01:00. The eruption continued until the 1st of May with a fluctuating tremor. The total volume of magma emitted during the eruption is hard to assess since a large amount of lava flowed down to the sea where it formed a large platform. However, given the topography and the bathymetry before the event, a volume of $\sim 100-140 \times 10^6$ m^3 has been inferred. This makes this eruption one of the most voluminous of PdF during the XXth and XXIth centuries.

3.2. Collapsed Structure

[9] Prior to the April 2007 eruption the summit zone of the central cone was occupied by a main collapsed structure, the Dolomieu crater. Historical reports reveal that it results from the coalescence of several pit craters aligned in the E-W direction [*Lénat and Bachèlery*, 1990; *Carter et al.*, 2007]. Before April 2007, the $\sim 74 \times 10^4$ m^2 structure (800 m wide and 1100 m long), was completely filled in by lava flows (Figure 4a).

[10] The April 2007 eruption led to the largest historical collapse of PdF, i.e., since 1760. Although the previous coalescent collapse structures were interpreted as pit craters [*Carter et al.*, 2007], we propose that the new structure, which is at least twice larger than the previous collapses is most akin to calderas. Indeed, the collaspe that is of the size of small calderas [*Geshi et al.*, 2002] directly influenced the magma chamber dynamics. The caldera was first recognized in the afternoon of April 6, about 16 hours after the beginning of the seismic cycles. Observations revealed that the collapse affected first the northern part of the pre-existing Dolomieu (Figure 4b). The new structure was elongated along an E-W direction and bounded by sub-vertical scarps in the E, N and W. Its geometry was about 200–300 m deep, ~1 km long and ~600 m wide. Two annular plateaus corresponding to the pre-existing floor of Dolomieu were remaining in the E and the S. On April 10 the caldera was enlarged to about the size of the pre-existing Dolomieu structure (i.e., 800 m wide and 1100 m long; Figure 4c), and deepened to ~330 m. Only few perched terraces remained from the collapse eastern plateau.

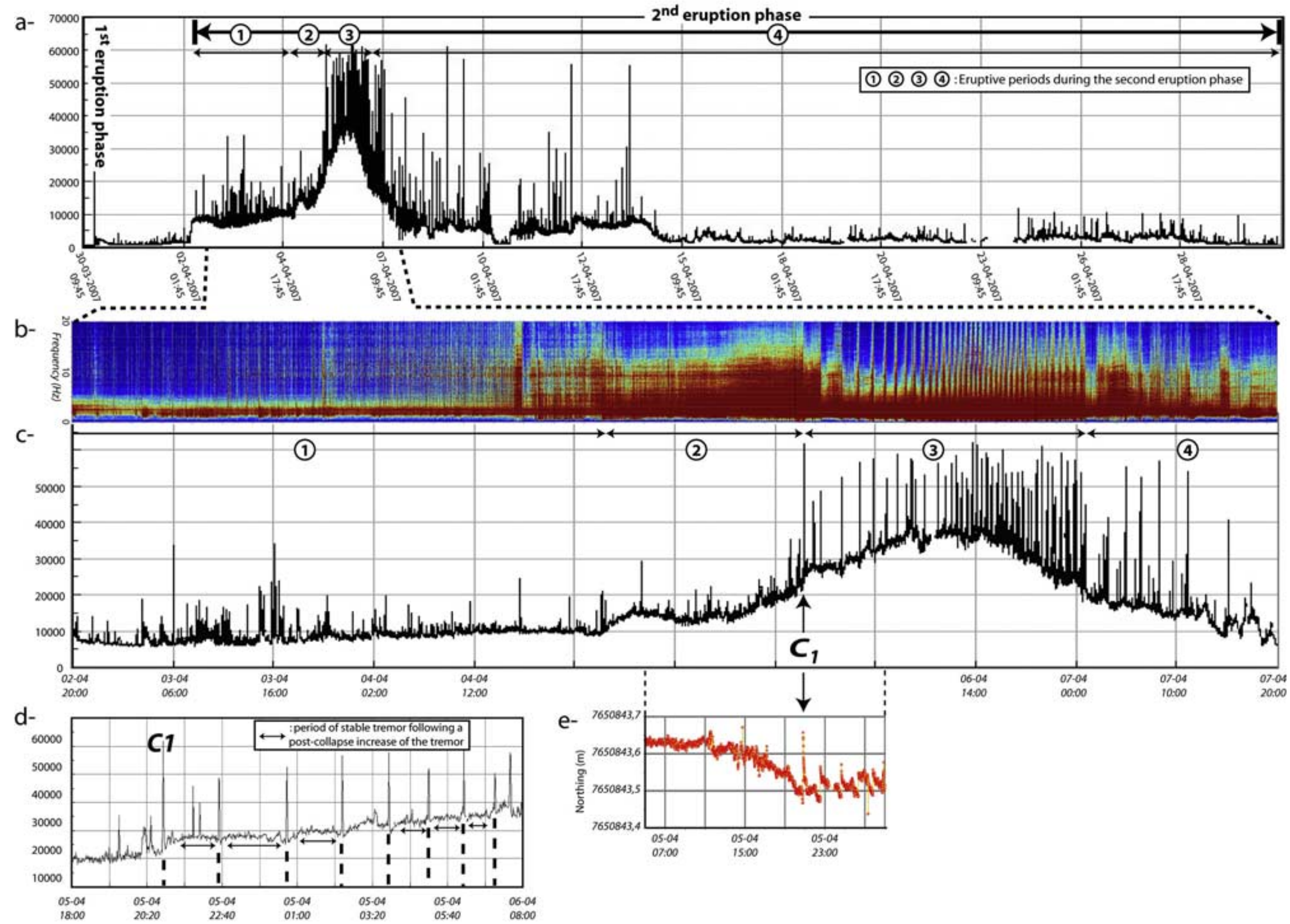

Figure 3. a) Eruptive signal recorded by the Takamaka seismic station. The peaks mark the VT events below the summit crater. b) Spectrogram of the seismicity recorded at the Bory seismic station for the pre-collapse and collapse periods. Red color between 0 and 5 Hz corresponds to the volcanic tremor. Red color between 5 and 15 Hz is interpreted as the vibration of the edifice during the stress accumulation. The short signals between 0 and 20 Hz indicate the VT events. c) Seismic signal recorded at Takamaka for the same period. C_1 is the initial collapse. d) Zoom of the seismic signal recorded at Takamaka illustrating the step-by-step increase of the tremor. e) N-S displacements recorded by the SNEG summit permanent GPS station (see Figure 1 for location).

[11] The geometry of the collapsed caldera did not significantly change after April 10. The size of the caldera increased by a few tens of meters with the lateral collapses of the western and north-western scarps along pre-existing concentric fractures already described by *Lénat and Bachèlery* [1990] and *Carter et al.* [2007]. The total area of the April 2007 caldera (82×10^4 m^2) is roughly similar to that of the pre-existing Dolomieu (74×10^4 m^2). This might be due to the fact that the collapse was mainly controlled by pre-existing concentric faults and/or that the magma chamber, the size and the location of which were recently determined from inversion of GPS data (diameters of 1.4 and 1 km in the E-W and N-S directions, and 0.3 km a.s.l. [*Peltier et al.*, 2007]) did not change since the XXth century. A maximum caldera depth of ~320–340 m was determined from triangulation, leading to a final volume of the caldera of 100–120 $\times$ 10^6 m^3. These values are confirmed by ASTER stereo images (M. Urai et al., Depression volume at Piton de la Fournaise volcano estimated by ASTER stereo imaging function, submitted to *Geophysical Research Letters,* 2007). Note that ~80% of this volume results from the early stage of the collapse, before the first observations on April 6.

4. Discussion and Conclusion

[12] The collapse of PdF is one of the few examples showing the direct impact of a caldera formation on the dynamics of the eruptive system. The collapse started three days after the onset of the second eruptive phase of the April 2007 eruption. Most of the deformation happened between April 5 and 6, and continued until April 10. During this time span, the seismic signal progressively increased. Summit GPS data reveal that the first collapse occurred on April 5 at 20:48, triggering a large VT event (C_1 in Figure 3). It happened after a 7 hours long period of inward deflation coeval with a progressive increase of the effusion rate at the eruption site, i.e., ~7 km away from the summit zone. The first collapse marks a change in the eruption dynamics. Figures 3c and 3d show that the increase of the seismic signal changed from continuous to step by step. The close temporal link between the following seismic cycles and the

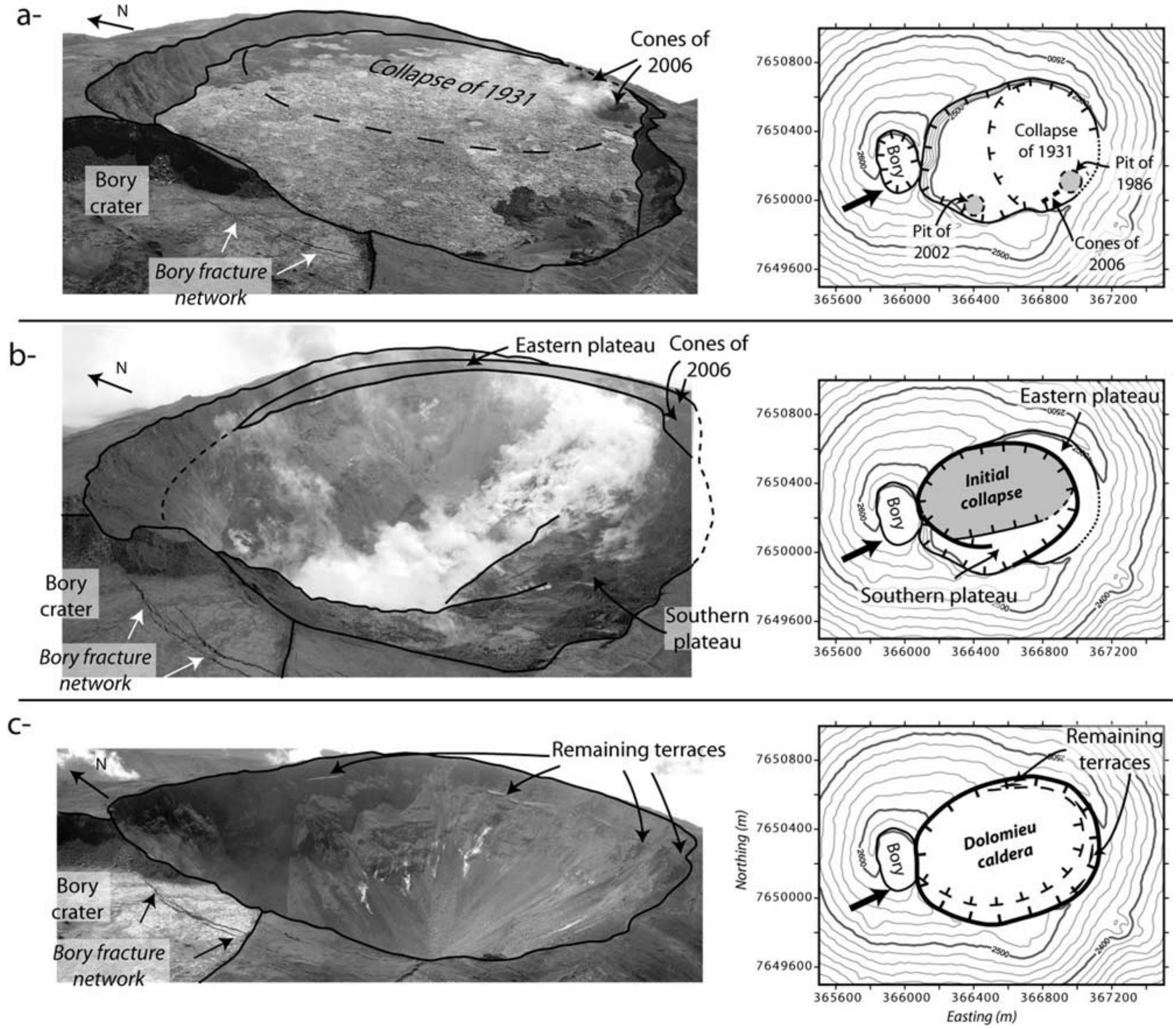

Figure 4. The Dolomieu crater on 31 October 2006 (a), on April 6 in the afternoon (b) and on April 10 (c). The Bory fracture network studied by *Carter et al.* [2007] in indicated for relocation.

step by step tremor intensification until 08:00 on April 6 strongly suggests a cogenetic origin. We propose that the slow increase of the seismic signal during each cycle corresponds to a stress build up in the overlying rock column beneath Dolomieu, which results from the progressive inward deflation of the summit zone. GPS and seismic data indicate that the sudden peak of each cycle denotes the collapse of the rock column. Likely, the GPS sudden outward displacements coeval with the collapses result from the collapse-related stress relaxation. We interpret the step by step increase of the seismic signal after the collapses as a consequence of the incremental overpressure in the magma reservoir. The decrease of the seismic signal amplification from April 6 08:00, after each seismic cycle, suggests that the effect of the collapses on the magma chamber vanished with time. Our data on the April 2007 collapse of Dolomieu confirm that this caldera collapse does not result from a single event but from the rapid succession of collapse events as already shown for Miyakejima [*Kumagai et al.*, 2001]. They also suggest that each cycle corresponds to a progressive stress accumulation due to the inward deflation followed by a rapid stress relaxation during the collapse.

[13] *Geshi et al.* [2002] showed that the caldera of Miyakejima formed progressively after the magma lateral intrusion. A similar scenario is proposed by *Simkin and Howard* [1970] to explain the caldera collapse at Fernandina. At PdF, the collapse occurred shortly after the beginning of the eruption when less than 30×10^6 m^3 of lava had been emitted. The volume difference of $60-70\times10^6$ m^3 between the collapse and the emitted magma when the collapse occurred may have several origins. 1- The beginning of the eruption was coeval to a large magma intrusion within the edifice leading to identical volumes of magma withdrawal and collapse. Usually the propagation of such intrusions triggers a clear seismic swarm [*Battaglia et al.*, 2005; *Aloisi et al.*, 2006]. At PdF, the seismic network recorded subtle northeastward and southeastward dike propagation few tens of minutes before the first eruption phase,

on March 30. However, its geometry can be hardly estimated with the deformation network of the OVPF, which is concentrated on and in the vicinity of the central cone. Hence, an intrusion likely occurred before the April 2007 eruption but its direct implication in the caldera collapse is hard to determine. 2- The collapse of the summit zone of PdF does not result from the April 2007 eruption only but is the consequence of the successive eruptions. We showed above that the final evolution of the distal and voluminous proximal eruptions changed since 2000 with the occurrence of an intense seismicity between the magma chamber and the summit during and after the last days or hours of eruptions (Figure 2). The abundance of the VT events, which indicates a deep deformation, was always coeval with an increase of both the tremor and the emission rates. However, it was never correlated with a surface deformation. The small pit crater formed in December 2002 after the November 2002 eruption is the only evidence of a subsurface deformation [*Longpré et al.*, 2007]. We propose that the co-eruptive final seismicity is related to a progressive collapse and weakening of the zone located above the magma chamber. In consequence, the caldera collapse at PdF could correspond to the surface deformation of a process which was initiated at depth several years ago.

[14] Therefore, we propose that the April 2007 caldera results from the combine effect of (1) an early intrusion, which substantially decrease the pressure in the magma reservoir during the first phase of the April 2007 eruption and (2) a progressive weakening of the rock column above the magma chamber since 2000.

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