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# The April 2007 eruption and the Dolomieu crater collapse, two major events at Piton de la Fournaise (La Réunion Island, Indian Ocean)

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ABSTRACT

After 10 years of high activity and 24 eruptions, Piton de la Fournaise (PdF) produced on April 2 to May 1, 2007 one of its most voluminous and intense eruption since at least one century. The eruption focused at 590 m elevation in the Grand Brûlé on the south east flank of Piton de la Fournaise, 7 km away from summit. It was located close to the southern cliff of the Grand Brûlé volcano tectonic collapse, the Rempart du Tremblet, and to the nearby village called Le Tremblet, and it highly rattled and incommoded the inhabitants there. Eleven hours after the beginning of the eruption the lava flows reached the sea and created 0.45 $km^2$ of new land until the end of eruption. In the night of April 5 the rock column beneath Dolomieu crater started to collapse with a piston like mechanism into the magma chamber, forming within less than 24 h the most recent and well documented caldera. We report in this paper the chronology of these two related major events in the recent activity of PdF seen by the scientific networks of the volcanological observatory (OVPF/IPGP) and field observations, which allowed to back up the scenario of the caldera formation and to quantify these two exceptional episodes.



## 1. Introduction —geological setting

Ile de La Réunion is located in the western Indian Ocean, 800 km east of Madagascar and represents the active centre of the 65 my old Deccan Trapp hotspot chain (Duncan, 1981; Morgan, 1981). The Island is formed by two shield volcanoes: the Piton des Neiges and the Piton de la Fournaise (Fig. 1). The older one, the Piton des Neiges erupted for the last time about 12 000 years ago (Deniel et al., 1992), whereas the Piton de la Fournaise, situated on the south east flank of Piton des Neiges, is still active. A third edifice, the completely eroded Alizés volcano, has been highlighted by magnetic and gravimetric campaigns (Malengreau et al., 1999; Lénat et al., 2001) in the in the Grand Brûlé area.

Three calderas characterize the evolution of Piton de la Fournaise: The first one formed about 150 000 years ago, with a remaining but highly eroded part limited by the Rivière des Remparts to the south. The second caldera formed about of 65 000 years ago (Gillot and Nativel, 1989; Staudacher and Allègre, 1993; Sarda et al., 1993) contains in its central part the Plaine des Sables and the upper Rivière de l'Est. The Enclos Fouqué represents the third caldera which was formed only 4500 years ago (Bachelery, 1981; Gillot and Nativel, 1989; Staudacher and Allègre, 1993), and where the majority of the recent eruptive activity took place.

Small collapses occurred in the recent period at PdF. Hugoulin (1860) and Lacroix (1936) describe the 1860 phreatomagmatic eruption, which was more intense in terms of emitted ash and rocks, but probably smaller in terms of collapsed volume than the April 2007 collapse (Maillard, 1862; Lacroix, 1936). From 1927, Dolomieu subsided progressively, forming finally in 1936 the 150 m deep Cratère Brûlant and the Enclos Vélain (Lacroix, 1939) with an estimated volume of about 0.05 $km^3$. Smaller pit craters formed in 1986 with a volume of 0.0014 $km^3$ (Delorme et al., 1989), and in 2002 with a volume of 0.0003 $km^3$, (Longpré et al., 2006).

Piton de la Fournaise is characterized by a high eruptive frequency, with a rate over the last 50 years of one eruption every 8 months (Peltier et al., 2009a-this issue). Several periods of high and low eruptive activity have been observed recently. Rest periods occurred from 1967 to 1971 and from 1993 to 1997. Very high activities were recorded during the periods from 1985 to 1988 and from 1998 to present.

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## 2. Research and monitoring network of the volcanological observatory

The **O**bservatoire **V**olcanologique du **P**iton de la **F**ournaise (OVPF) is in charge of the volcano monitoring and research on the Piton de la Fournaise since 1980. Two main networks (seismic and deformation) are implemented. The seismic network is currently composed of 25 seismic stations equipped with vertical or 3 components 1 Hz geophones or large band sensors. The network (Fig. 2) is organised in four circles centred around the summit, three summit stations are located around the border of Bory and Dolomieu craters, five stations are located at the base of the summit cone of the volcano at about 1.5 km from the summit and three stations are located on the rim of the Enclos Fouqué caldera (4 to 5 km from the summit). Several stations are at larger distance (not shown in Fig. 2). The seismic network thus covers the whole Piton de la Fournaise massif.

The deformation network comprises 12 permanent GPS stations and 7 tiltmeter stations (Fig. 2). The GPS network consists of three Trimble NetRS, seven Topcon GB-1000 and two Ashtech Zxtreme, which record their position every 30 s. Five GPS are located around the summit craters (SNEG, DERG, DSRG, BORG and BONG, G indicates GPS), five others are located at the base of the summit cone (FJSG, FERG, FORG, RIVG and CHAG) and two are located on the Enclos Fouqué caldera rim (GITG and ENCG). Data of four stations (BONG, SNEG, GITG and ENCG) are directly transmitted to the observatory, while the remaining stations store data in the field. Usually data are recovered every 1 to 2 months, but more often in case of seismic crisis or eruptions. Two stations, BONG and SNEG are in a real time cinematic survey mode and send their position to the OVPF every second.

The tiltmeter network (Fig. 2) consists of 7 Blum type instruments (Blum, 1963). Three are located around the summit craters (SFRI, BORI and DSRI, I indicates tiltmeter), three others are located at the base of the summit cone (FERI, TCRI and FORI) and a final one at crater Catherine (CATI), in the southern part of the Enclos. Unfortunately SFRI was out of service due to the strong deformation at the time of

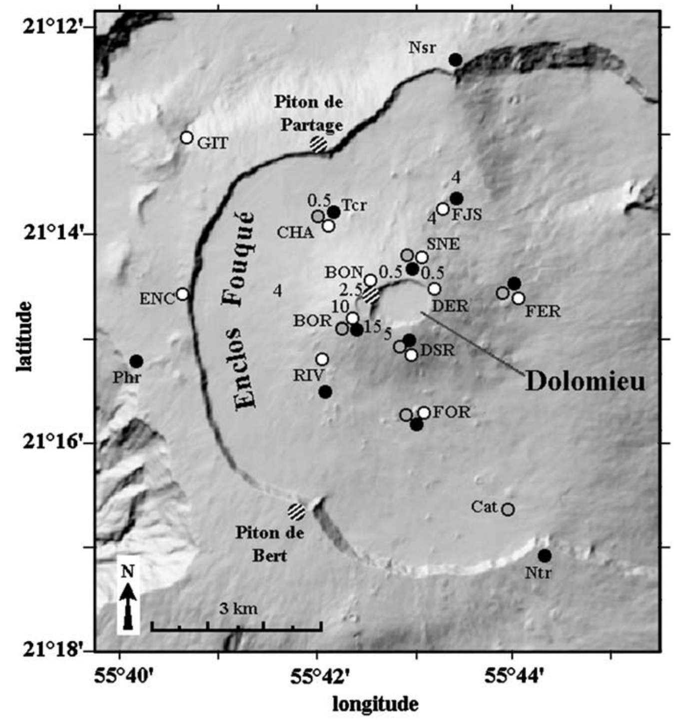


**Fig. 2.** Research and survey network of the Observatoire volcanologique du Piton de la Fournaise. Black dots represent seismometers, black circles filled grey are tiltmeter stations, black circles filled white are the permanent GPS stations. Black and white dots are webcams. SNE = Soufrière north east; DER = Dolomieu East; DSR = Dolomieu South; BOR = Bory; BON = Bory north-west; CHA, Tcr = Tunnel Catherine; FJS = Faujas; FER = Flanc Est; FOR = Château Fort; Cat = Cratère Catherine; Ntr = Nez Coupé de Tremblet; Phr = Piton Hubert; ENC = enclos, GIT = Gîte du Bellecombe; Nsr = Nez Coupé de Sainte Rose. Latitude and longitude are given in WGS84 coordinates. Numbers represent thickness of ash deposits measured on April 10, 2007 derived from the Dolomieu collapse (see Section 5.2).

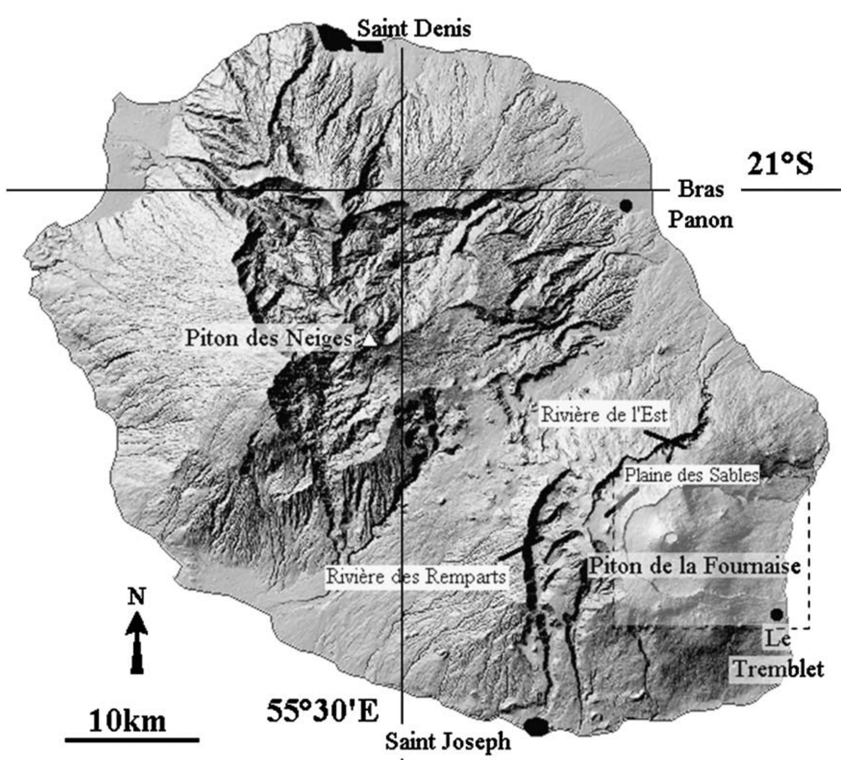


**Fig. 1.** DEM of Ile de La Réunion. Indicated are the main locations cited in the paper as well as the Piton de la Fournaise area.

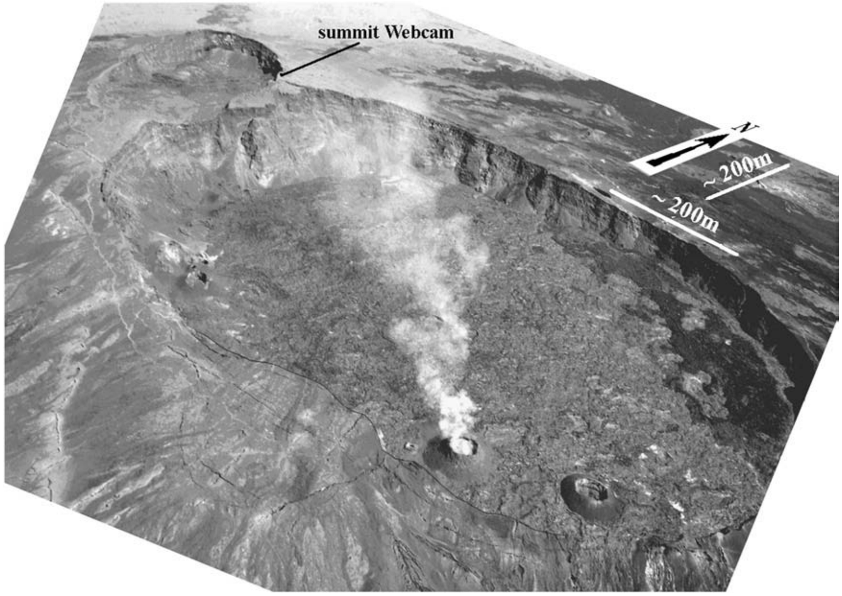


**Fig. 3.** Dolomieu crater brimful on October 31, 2006. The crater floor was entirely recovered by an up to 30 m thick lava flow, which even overflowed to the east flank.

the March 30 eruption. FORI was destroyed during the July 2006 eruption. Tiltmeters have sampling rates of 1 pt/mn and the data are transmitted to the OVPF every 5 min.

Finally, three webcams are installed in the field, two on the Enclos Fouqué caldera rim to the north at Piton de Partage and to the south at Piton de Bert (Fig. 2). A third one was located on the western Dolomieu rim looking into the Dolomieu crater, but felt into the Dolomieu during a large landslide of the crater rim on May 23, 2007. Pictures are sent to the observatory every minute.

## 3. Pre-eruptive activity

After the August 30, 2006 to January 1, 2007 eruption, which full filled the whole Dolomieu crater (see Fig. 3) with about $20 \times 10^6$ $m^3$ of lava (Staudacher et al., 2008; Peltier et al., 2009a-this issue) on a thickness of up to 30 m in the eastern part of the crater, the OVPF deformation network recorded a continuous inflation of the summit cone. On February 18, after a 27 min seismic crisis beneath Dolomieu crater, a small summit eruption took place at 14h38 GMT in Dolomieu crater (Fig. 4) along a straight west–east fissure. The eruption ended the following day at 5h00 GMT after less than $1 \times 10^6$ $m^3$ of lava emission. In spite of the occurrence of this small eruption, the summit of the volcano kept on inflation (Peltier et al., 2009b-this issue) and on March 30 at 16h23 GMT a new 145 min seismic crisis occurred beneath the summit (Fig. 5). The permanent GPS network and the seismicity indicated first an intrusion toward the north-east flank, before to highlight a main magma injection to the South-East (Peltier et al., 2009b-this issue). A flank eruption started at 18h50 GMT at 1900 m elevation on the South-East flank (Fig. 4). Eruptive tremor disappeared the following morning at 5h15. Lava emission was small with less than $1 \times 10^6$ $m^3$. The eruption was accompanied by very strong seismic activity beneath the summit which persisted after its end and increased continuously until April 2.

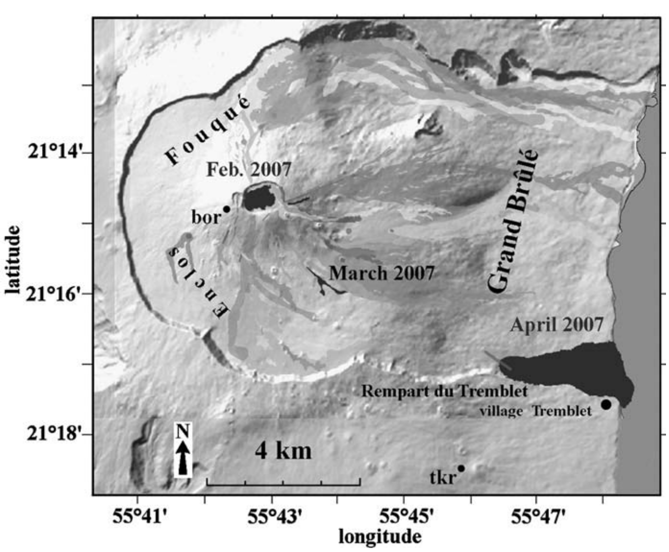


**Fig. 4.** The 2007 eruptions. The 2007 eruptive activity started with a short 14 h lasting summit eruption on February 18, which was followed by a second short, 10 h lasting flank eruption on March 30 and ended with a distal eruption from April 2 to May 1 at 590 m elevation, 7 km away from summit. bor and tkr are the Bory and Takamaka seismic stations.

## 4. The April 2007 eruption

### 4.1. Chronology

On April 2, eruptive tremor started again at 6:00 GMT revealing the renewing of eruptive activity. The eruption vent was located 7 km East-South-East from the summit in the Grand Brûlé along a 1 km eruptive fissure (Fig. 4). Rapidly the eruptive activity focused at 590 m altitude on its lower end (55°46′25.5″; −21°16′54.6″, WGS84), 400 m away from the Rempart du Tremblet. Two lava flows went down the slope and reached the national road (Fig. 6) located 2.5 km further down slope at 11h15 and 12h15. At 17h25 the first lava flow entered into the sea. At the end of the first day, the two lava flows already covered the national road over a length of several hundreds of meters.

Eruption intensity was very high, with lava fountains reaching a height of 100 to 150 m and sometimes several tens of individual lava flows. Both characteristics are unusual for Piton de la Fournaise eruptions, where lava fountains only reach 50 to 100 m during the early eruptive phase. On April 6, concomitant to the Dolomieu collapse (see below), lava fountains reached more than 200 m high. In the following several tens of individual lava flows were observed in the Grand Brûlé, being 2 to 20 m wide, 1 to 3 m thick, with velocities of 1 to 2 m $s^{-1}$. The lava outflow on April 6 was estimated to be greater

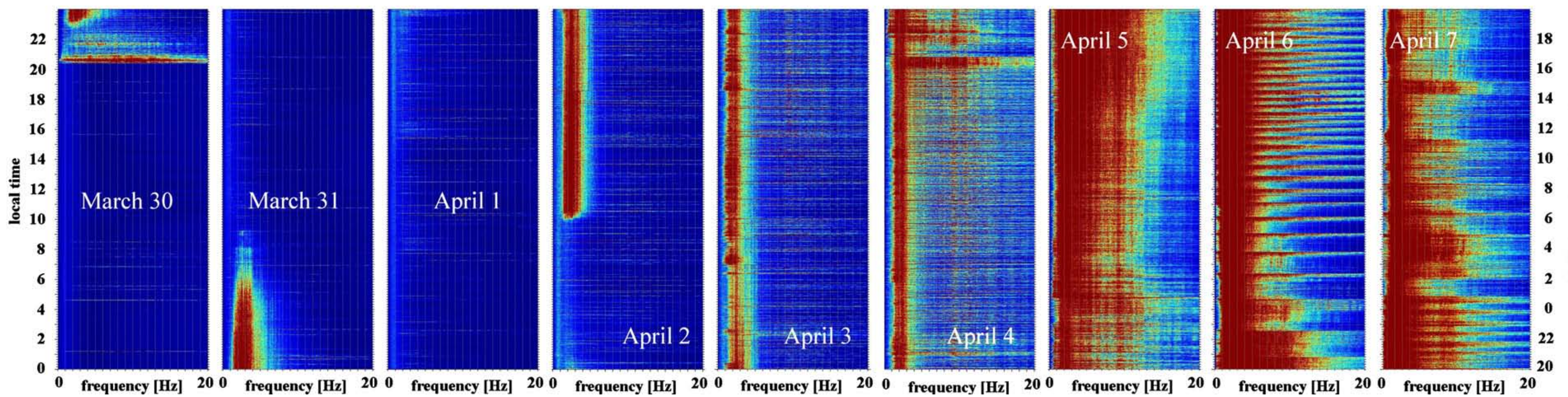


**Fig. 5.** Spectrograms of the Bory seismic station. The spectrograms cover the March 30 and the early April 2 eruptions, as well as the Dolomieu collapse. Eruptive tremor is represented by brownish colour; volcano-tectonic seismic events with large spectra are shown as horizontal lines. The left *y*-axis represents the local time, the right *y*-axis represents GMT (GMT = local time − 4). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

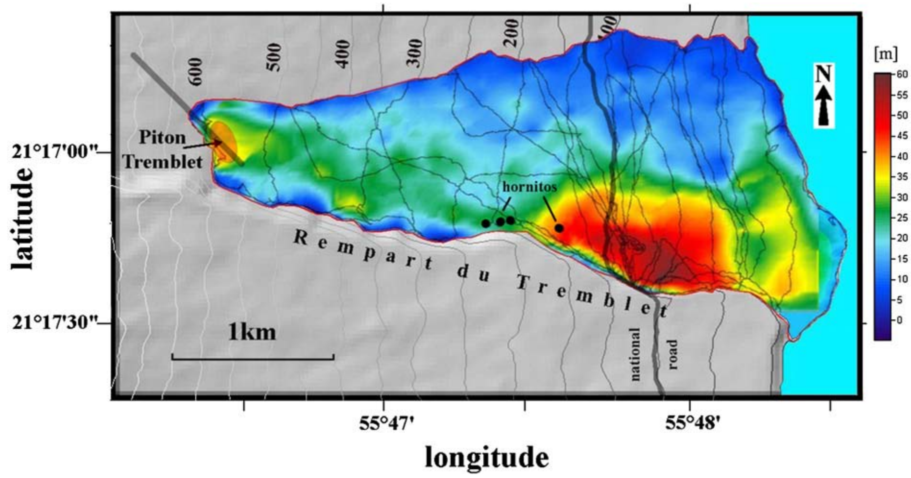


**Fig. 6.** The April 2007 lava flow. Shown are colour coded thickness of the lava flow, determined by cinematic GPS measurements and subtraction from a pre-existing DEM. Black curves represent the post-eruption GPS campaigns on the lava flow.

than 200 $m^3 s^{-1}$. This value is a low estimation due to the hidden out flow within lava tubes which could not be taken into account.

During the course of the eruption, the lava flow continuously enlarged to the north (extreme points: 55°47′39″; −21°16′40″) and to the south (55°47′51″; −21°17′26″) were it was guided by the caldera rim. It finally formed a single huge flow of about 1.8 km wide at the coastline and covered 1.4 km of the national road (Fig. 6). Most of the lava flows are aa type, in particular in the northern and upper parts. On April 11, hornitos formed over a lava tunnel close to the Rempart du Tremblet at 290 m elevation (55°47′29″; −21°17′12″) and another one on April 23 at 180 m altitude (55°47′36″; −21°17′13″) flooding the area below by successive lava flows piling up to more than 60 m in thickness.

Eruptive tremor almost disappeared on April 30 and the eruption stopped on May 1, but hot spots up to 780 °C, measured using a FLIR 695 infrared camera, had been observed inside deep fractures and pits, more than 1 year after the end of the eruption.

### 4.2. Nature of lavas and gas emission

During the whole eruption, the lava was regularly sampled. From April 2 to April 4, the lava was poorly phyric with less than 5% of small phenocrysts of olivine–clinopyroxene and plagioclase. From April 5, the amount and the size of olivine crystals (up to one centimetre) increased, reaching at the end of the eruption a picritic composition with up to 30% of olivine phenocrysts (Villemant et al., 2009-this issue).

The eruption emitted large amounts of volcanic gases from the eruptive fissure but also from the sea, where a huge plume elevated at the entry of the lava in water. $SO_2$ clouds were observed from space by the EOS OMI/Aura instrument in the western Indian Ocean (OMI website). Ground measurements, close to the eruption site, showed $SO_2$ concentrations of up to 2500 μg/$m^3$ punctually. The long term averaged concentrations were lying between 38 and 379 μg/$m^3$ over 7 to 10 days (Bhugwant et al., 2009-this issue).

When the lava entered into the sea explosive interactions have been produced, forming an acidic steam plume, transporting tephra and molten fragments up to 1 km away from the sea. Up to 1 cm thick deposits of micro- to several millimetres sized fragments of basaltic glasses, olivine crystals and Pele's hairs, covered by Na + Cl, Ca + S and Mg + S rich crystals, were sampled at the Tremblet village near the eruption site (Aubaud and Besson, 2007). Pele's hairs were found abundantly in the south-eastern part of the island from St. Joseph to Bras Panon and in minor amounts until St. Denis in the north (Fig. 1). The steam plume, combined with the $SO_2$ rich eruption plume formed acidic rain over the southern part of the island, reaching pH values inferior to 2 (Bhugwant et al., 2009-this issue).

### 4.3. Magma production

From field observations it was evident that the April 2007 eruption was particularly intense in term of lava outflow, flow thickness and erupted volume. In order to estimate the emitted volume with precision, we carried out cinematic GPS measurements on the lava flow immediately after the end of the eruption (Ashtech Zxtrem or Topcon GB1000 GPS instruments recording one data per second). For these differential GPS measurements, we used as reference station a geodetic point 2A48 (55°48′04.36″; −21°18′05.22″, 110.482 m; OVPF internal data) located close to the Grand Brûlé about 1.5 km away from the April lava flow. Data precision during walking was estimated from the RMS value given by the data reduction to <20 cm in the three dimensions. A computer program developed by Eychenne (2007) allowed us to calculate automatically the difference in elevation between a pre-existing digital elevation model (DEM) and the new cinematic GPS data, and to determine precise volume estimation and volume distribution over the whole lava flow on land.

Fig. 6 shows the distribution of the thickness of the lava field. About 50% of the northern part shows a thickness ranging between 10 and 20 m and represents mostly aa type lava flows. Downhill of the eruptive site and all along the Rempart du Tremblet, the lava thickness varies between 30 and more than 60 m. This part is mainly covered by pahoehoe type lava flows and contains numerous lava tubes up to 10 m in diameter (Deroussi et al., 2009-this issue). Break out of lava tubes and several hornitos allowed the superposition of numerous strata and an accumulation of the lava flow to more than 60 m high. The eruption flooded 3.8 $km^2$ of the Grand Brûlé and produced there a total of $90 \times 10^6$ $m^3$ of lava.

On the sea, a 0.45 $km^2$ large platform builds up over the whole front of the lava flow with a maximum length to 370 m. Taking into account the sea floor bathymetry and a slope for the lava flow front on the sea floor of 30 to 35°, we can estimate that about $40 \times 10^6$ $m^3$ of lava went to the sea. Thus the total volume of the April 2007 lava flow can be estimated at about $130 \times 10^6$ $m^3$.

From this volume estimation and the duration of the eruption, we obtain a mean eruption rate of 52 $m^3 s^{-1}$. The total volume and the mean flux are extreme values for recent Piton de la Fournaise eruptions (Vlastelic et al., 2007; Staudacher et al., 2008). A similar volume is only reported for the 1931 eruption, which emitted $130 \times 10^6$ $m^3$, and for the 1998 eruption, which emitted $60 \times 10^6$ $m^3$ (Staudacher et al., 1998). Mean erupted volumes and lava flow rates

**Table 1**
Deformations recorded by the permanent GPS on April 5 during Dolomieu collapse in cm. *x* corresponds to a west–east movement; *y* corresponds to a south-north movement.

| Time range | BORG | | BONG | | SNEG | | DERG | |
|---|---|---|---|---|---|---|---|---|
| | *x* | *y* | *x* | *y* | *x* | *y* | *x* | *y* |
| 12:00–20:48 | 8 | 3 | 13 | −8 | −7 | −13 | −15 | −2 |
| 20:48–20:50 | −10 | −1 | −12 | 8 | 15 | 18 | 41 | 14 |
| 20:50–22:33 | 8 | 4 | 12 | −8 | −12 | −17 | −25 | −11 |
| 22:33–22:34 | −3 | −1 | −5 | 3 | 5 | 8 | 11 | 3 |

range at Piton de la Fournaise usually around $10\times10^6$ $m^3$ and 1 to 15 $m^3$ $s^{-1}$, respectively. None of the oldest inhabitants living close to the Grand Brûlé could remember such an intense eruption.

## 5. The Dolomieu caldera formation

### 5.1. Seismic, GPS and tiltmeter observations

As mentioned above, the April 2007 eruption was accompanied by a continuous seismic crisis located under the central cone and a constant increase of the lava flux up to a paroxysmal phase on April 6. The seismicity under the summit of PdF increased continuously from April 4 to April 6 (Fig. 5).

The increase of seismic tremor was accompanied on April 5 from 12:00 to 20:48 by an inward motion and deflation of the Piton de la Fournaise summit; 9 to 15 cm and 6 cm were recorded on the horizontal and vertical GPS components, respectively (Table 1 and Fig. 7). Unfortunately the Dolomieu Sud GPS (DSRG) had a power failure at that moment. The inward motion was centred below the Dolomieu crater (black arrows in Fig. 7).

On April 5 at 20:48 GMT, a 3.2 $M_d$ seismic event occurred. At the same time a sudden decrease of the seismicity beneath the summit of PdF was observed. From 20:48 to 20:49 a strong summit deflation was recorded by the BORI tiltmeter (1050 µrad), followed by a huge inflation within the next 2 min (1090 µrad) (Fig. 8). The permanent GPS recorded horizontal displacements of 10, 14, 23 and 43 cm at BORG, BONG, SNEG, and DERG respectively (white arrows in Fig. 7, Table 1), but no significant vertical displacements were recorded. Displacement vectors point radial away from the Dolomieu centre (white arrows in Fig. 7) with an origin which is coherent with the deflation centre recorded between 20:48 and 20:49. Both agree perfectly with the deepest area of the Dolomieu caldera (as determined by Urai et al., 2007), which is slightly north of the physical centre of Dolomieu crater. Only the vector for BONG points slightly south of it.

Immediately after April 5, 20:49 GMT, the seismicity increased again, the BORI tiltmeter and the GPS network showed a new deflation until 22:34 (Fig. 9), followed by a sudden decrease of seismicity and a new inflation, (see dark grey arrows in Fig. 7). Such systematic cyclic variations continued over more than 48 h lasting from about 2 h in the beginning to 30 min at the end. As we could observe by the OVPF webcam, each cyclic variation ended with ash plumes coming out of the Dolomieu crater (see example in Fig. 10: April 6, 12:38).

### 5.2. Ash emission

On April 10, a field campaign to the summit allowed us to collect ash samples around the summit craters and to measure the thicknesses of the ash deposits (see Fig. 2). Ash deposit thicknesses ranged between less than 1 mm to 15 mm at the West-South-West of the summit craters, close to the Bory GPS station, and around 5 mm at the south and the north of Dolomieu crater. Preliminary petrologic studies of these samples showed that they represent exclusively phreatic ash with no new lava involved (Ph. Mairine, pers. communication), revealing that no phreatomagmatic explosion occurred during Dolomieu collapse.

### 5.3. Webcam observations

Unfortunately, weather conditions during the Dolomieu collapse, on April 6 were extremely bad, with clouds over the volcano and dense fog in the Dolomieu crater. Fig. 10 shows a selection of pictures taken by the Bory webcam on the West-North-West rim of Dolomieu. April 5, 11:49 (GMT) was the last view of Dolomieu crater showing the lava flooded crater resulting from the August 2006 and February 2007 eruptions. On April 5, 17:06 the illumination of the sky by the distal April eruption was visible. On April 6, 2:14, the window in front of the

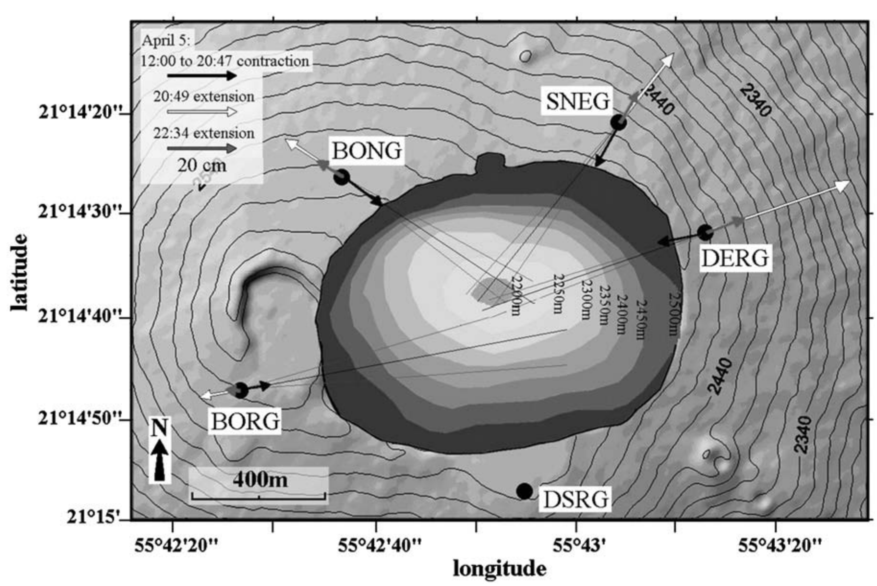


**Fig. 7.** Displacement vectors of permanent GPS summit stations. Black arrows represent the inward motion on April 5 from 12:00 to 20:47, white arrows represent the extension of the Dolomieu crater on April 5, 20:49, and grey arrows represent the extension on April 5, 22:34. BONG, SNEG and DERG displacements point to or diverge from the centre of Dolomieu collapse. The vertical contour levels inside the Dolomieu craters with a distance in elevation of 50 m are plotted after Urai et al. (Urai et al. (2007, Fig. 3). The lowest point is at about 340 m below the east border of Dolomieu.

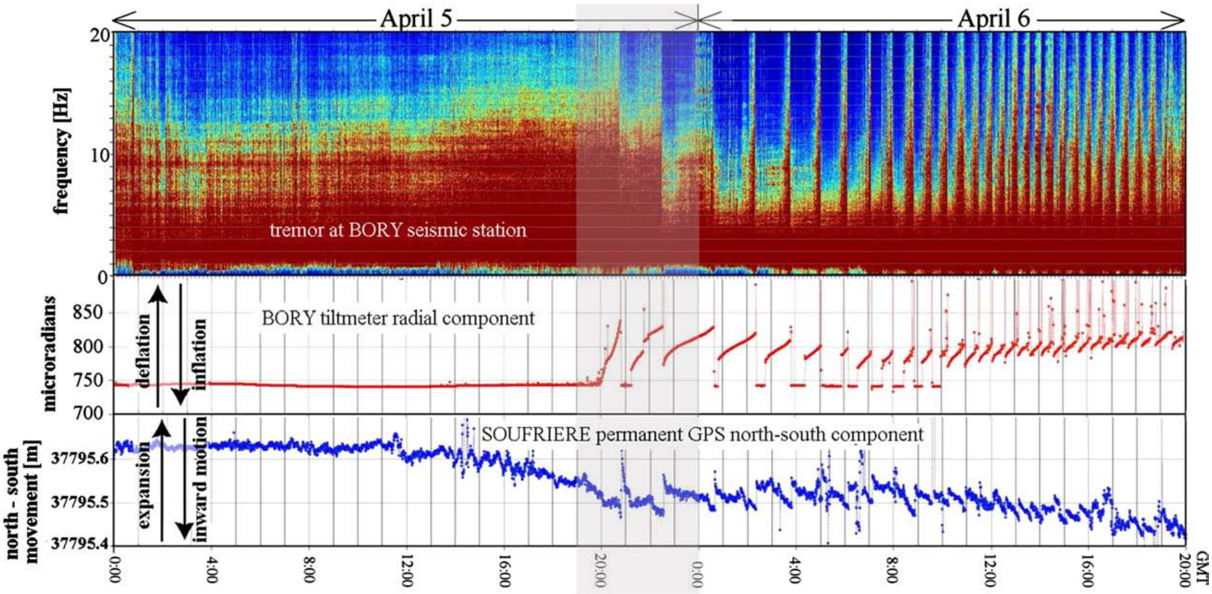


**Fig. 8.** Spectrogram and deformation plot of April 5 to April 6. Top: spectrogram of seismic tremor during April 5 and 6; middle: radial component of the Bory tiltmeter station; bottom: Soufrière permanent GPS North–South component. Note the close correlation between tremor intensity, tiltmeter and GPS movement starting on April 5 at 20:48 and lasting until early April 7. Greyish area corresponds to the time window shown in Fig. 9.

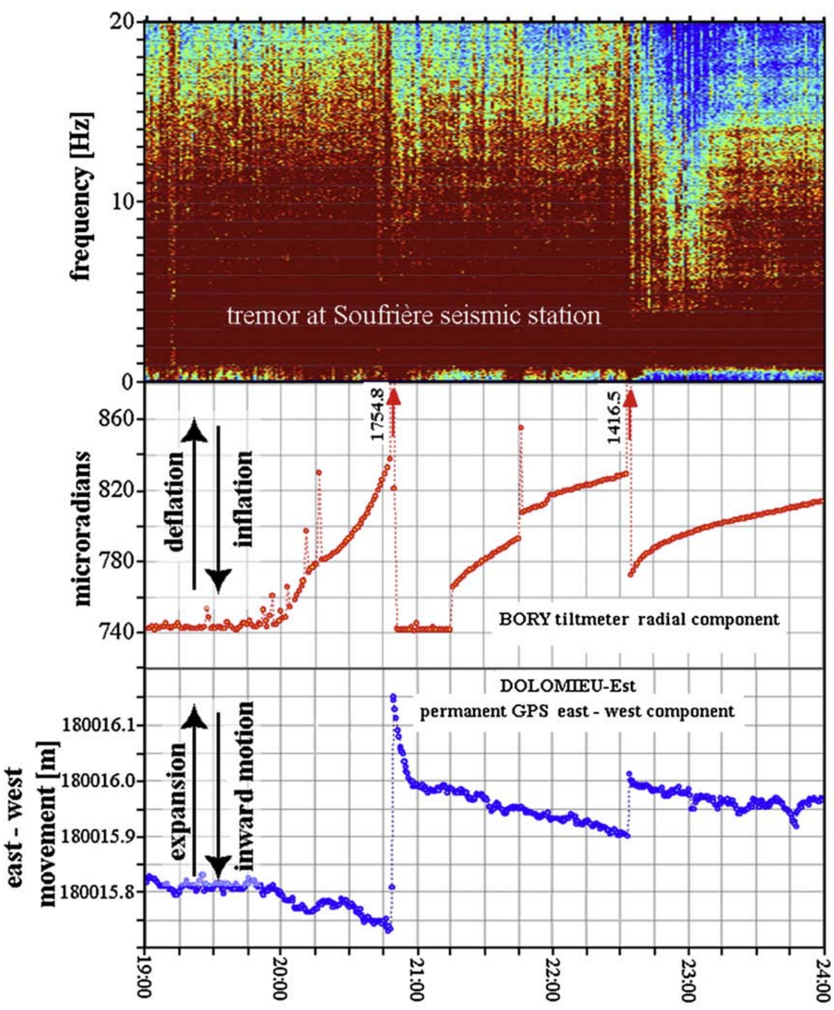


**Fig. 9.** Enlarged spectrogram and deformation plot. This representation covers of the period on April 5 between 19:00 and 24:00 revealing the close correlation between tremor recorded by the Soufrière seismic station, tilting and the Dolomieu-Est permanent GPS station. Note that the tiltmeter maximum values were out of range and the values are indicated in the plot.


**Fig. 10.** Dolomieu webcam pictures. On the upper left is shown the location of the webcam and the sector of the Dolomieu crater covered by the webcam.

webcam was covered by dust, but fog avoids us to distinguish more details. The view at April 6, 12:04 was the first one showing the collapsed Dolomieu crater. The eastern plateau as described by Michon et al. (2007) with the August 2006 eruption cones was still present and the southern plateau (Michon et al., 2007) has slipped down some tens of meters. At April 6, 12:38 an ash plume from the northern Dolomieu appeared and at 14:33 on the same day, remaining lava pockets from the August 2006 eruption, still liquid and stored beneath the surface, produced some small lava flows falling into the eastern part of the Dolomieu crater collapse and were visible until April 7. On April 7, 7:03 the August 2006 eruption cones have disappeared and the terraces beneath the eastern rim had glided down some more tens of meters. From these pictures it is evident that the main collapse occurred after April 5, 17:00 and before April 6, 12:00 GMT. In the following days the diameter of the collapse slightly increased, remaining terraces (see above) glided down. It is however not clear whether the Dolomieu caldera reached its final depth at that moment or if the bottom of the caldera dropped down over a longer period. Landslides inside the Dolomieu occurred within the next days and weeks. The Bory webcam itself collapsed into the crater on May 24, 23:01 after a new subterranean collapse. Fig. 11 shows the new 340 m deep Dolomieu caldera seen by helicopter from the South-East on April 10, 2007. At around 200 m below the caldera rim, wet gravel and rocks and vapour are visible (see black and white arrows in Fig. 11). This may indicate a water table showing on April 17, 2007 temperatures between 133 °C on the East part and up to 230 °C on the West-South-West part, measured by a FLIR 695 infrared camera.

### 5.4. Depth, dimension and volume determination

Rapidly after formation of the Dolomieu collapse first investigations have been performed in order to determine the depth and the

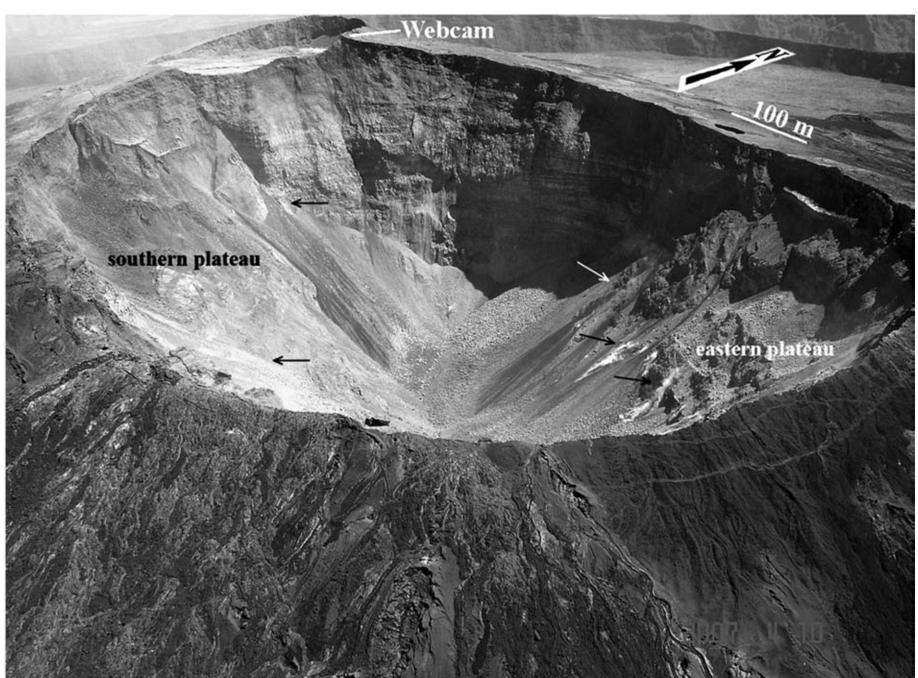


**Fig. 11.** The Dolomieu caldera on April 10, 2007. The crater floor has disappeared revealing a 340 m deep and 1030 over 870 m large caldera.

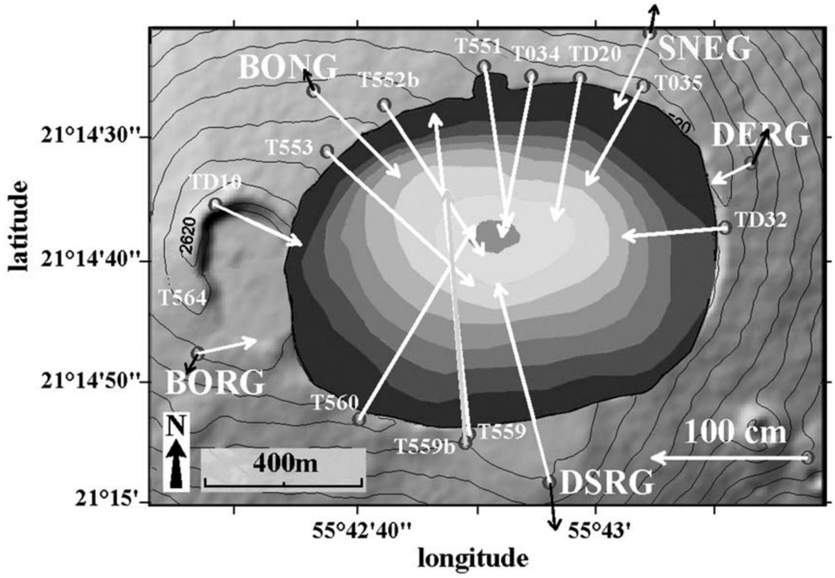


**Fig. 12.** Pre- and post-collapse ground displacements of the Piton de la Fournaise massif. Shown are the horizontal ground displacements as recorded by the permanent (large characters) and punctual GPS network (small characters). Black arrows represent pre-eruptive and pre-collapse expansion of the Dolomieu crater recorded by the permanent GPS network, while white arrows represent post-collapse inward motion of the crater from April 6 to end of November 2007.

extension of the collapse. Due to the instability of the crater rims, only quick distance measurements using a Leica telemeter allowed us to estimate its size. Length and angle of incident measurements had been performed at about 20 sites around the crater.

Four days after its collapse, the size of the Dolomieu caldera was 1030 m along an East West direction and 870 m along a North South direction. The depth relative to the lowest eastern border of Dolomieu is $340 \pm 15$ m (mean value of 20 measurements). New measurements in mid-2008 showed the same results, revealing that the small landslides occurring since the collapse did not significantly change its size or depth. The lowest point of the caldera is located at about 2150 m elevation, and in good agreement with the depth of $320 \pm 20$ m estimated by Urai et al. (2007) using ASTER stereo imagery.

Based on a simple cone shape, we found a volume of the collapse equal to $78 \times 10^6$ m$^3$, which represents a lower limit of the volume of the Dolomieu caldera. If we take into account the caldera morphology as determined in Urai et al. (2007), (see also Fig. 7) the volume of the Dolomieu caldera represents about $90 \times 10^6$ m$^3$.

**Table 2**
Horizontal and vertical movements related to the Dolomieu crater collapse, recorded by the permanent (bold characters) and punctual GPS network.

| Point | East shift (m) | North shift (m) | Up lift (m) |
|---|---|---|---|
| **SNEG** | −0.208 | −0.459 | −0.267 |
| T035 | −0.357 | −0.614 | −0.384 |
| **DERG** | −0.240 | −0.121 | −0.208 |
| TD32 | −0.642 | −0.056 | −0.449 |
| **DSRG** | −0.324 | 1.233 | −0.674 |
| T559 | −0.119 | 1.598 | −0.853 |
| T559b | −0.227 | 2.010 | −0.989 |
| T560 | 0.714 | 1.214 | −0.923 |
| **BORG** | 0.358 | 0.075 | −0.233 |
| TD10 | 0.530 | −0.257 | −0.357 |
| T553 | 0.919 | −0.846 | −0.672 |
| **BONG** | 0.538 | −0.545 | −0.389 |
| T552b | 0.625 | −0.939 | −0.476 |
| T551 | 0.149 | −1.000 | −0.435 |
| T034 | −0.187 | −1.003 | −0.551 |
| **TD20** | −0.154 | −0.896 | −0.548 |

### *5.5. Post-collapse readjustment of the Piton de la Fournaise summit*

Following the Dolomieu collapse, the summit of Piton de la Fournaise deflated significantly. Fig. 12 shows GPS data (Table 2), recorded on the summit stations from March 30, 2007 to end of November 2007. Dark arrows in Fig. 12 show the pre-eruptive extension of the summit, as recorded by the permanent stations DERG, SNEG, BONG, BORG and DSRG, respectively. White arrows show the inward motion of Dolomieu crater after the beginning of the April 2007 eruption and the collapse, recorded by the permanent and punctual GPS network. We observed deflation between 27 and 99 cm and horizontal motions between 27 cm and 2 m. Note that 95% of the post-collapse deformation took place during the first 3 months and the remaining 5% during July to November 2007. All arrows converge to the centre of Dolomieu.

## 6. Discussion

### *6.1. Interaction between eruption and caldera formation*

Between 1998 and 2007, Piton de la Fournaise volcano displayed a high eruptive activity with 25 eruptions (Staudacher et al., 2008; Peltier et al., 2009a-this issue). The initial scenario of each eruption is similar, with a first vertical dike intrusion below the Dolomieu crater (Peltier et al., 2005). Either these dikes get through up to the summit, leading to summit eruptions, or start to progress horizontally at about 1000 m elevation leading to lateral eruptions (flank or distal eruptions according to the distance from the summit). It seems evident that such an intense eruptive activity with the injection of numerous dikes highly fractured the rock volume between the shallow magma chamber and the summit. Furthermore, since 2001 the ending phases of lateral eruptions were always accompanied by volcano tectonic earthquakes above sea level under the central cone. Until March 2007, the whole rock column was still supported by the pressurized magma chamber. On April 2, the distal eruption started in the Grand Brûlé at only 590 m elevation, approximately at the same level as the shallow magma chamber (Peltier et al., 2007). Consequently the hydrostatic pressure beneath Dolomieu crater decreased and by the way destabilized the rock column between Dolomieu crater and magma chamber leading to the collapse into the latter (Fig. 13).

The analyses of seismic, tiltmeter and GPS data (Figs. 8 and 9) suggest that the Dolomieu collapse occurred in the following way.

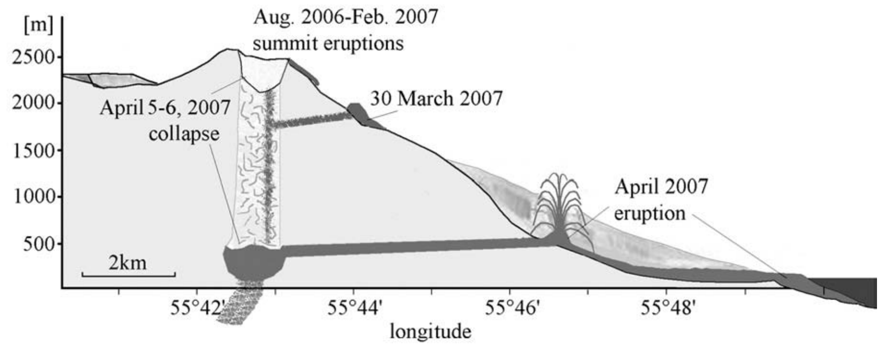


**Fig. 13.** Cross-section through the Piton de la Fournaise massif. This sketch describes the succession of intrusive and eruptive events between August 2006 and April 2007, followed by the caldera formation.

Fig. 14a shows the situation before the April 2007 eruption. The 2000 m high rock column between the Dolomieu crater and the shallow magma chamber located around 300 masl (Peltier et al., 2007, 2009b-this issue), was supported by the pressure in the magma chamber. From April 2 to April 5, the eruption in the Grand Brûlé tapped laterally magma with a high outflow rate from the shallow magma chamber and decreased the pressure there. On April 5 in the morning, the 2000 m rock column was drawn downwards by gravity by a piston like mechanism (Lipman, 1997; Roche et al., 2001) but it was still wedged by the surrounding bedrock of the massif (Fig. 14b, c). Seismic tremor continuously increased and the Dolomieu border was deflated, pulled down-wards, thus lowering the diameter of Dolomieu crater by about 20 cm (Fig. 7). On April 5, 20:48 the whole rock column slipped down suddenly, thus releasing the outer border of the Dolomieu crater (Fig. 14d) and generated a 3.2 $M_d$ seismic event. Simultaneously seismic tremor decreased, the summit inflated and permanent GPS indicated an extension of Dolomieu of about 50 cm (Figs. 7–9). The same process repeated during the next 48 h, forming numerous cycles of increasing eruptive tremor and surface deformation (Fig. 8).

The influence of the Dolomieu collapse on the magma chamber and consequently on the ongoing the eruption can be derived from Fig. 15. Here we plotted the averaged seismic noise amplitude recorded between April 1 and April 20 on tkr and bor seismic stations located respectively near the eruption vent and the summit collapse (see Fig. 4). Even if it is difficult to separate the seismic activity at the summit of the volcano from the eruption tremor, it is clear that the main collapse event recorded by the Bory seismic station (bor) occurred about 12 to 24 h before the maximum seismic noise recorded by the Takamaka seismic station (tkr). This temporal correlation seems to indicate that the increase of the summit activity related to the Dolomieu collapse has triggered the increase of the eruptive activity, i.e. tremor increase recorded on the tkr seismic station (see arrows in Fig. 15).

### 6.2. Caldera formation and erupted lava volume

Geyer et al. (2006) related the erupted volume fraction (volume of extruded magma over total volume of magma chamber) required to trigger a caldera collapse $f_{crit}$, as a function of the chamber aspect ratio r (the depth over the diameter of the chamber). In our case $f_{crit} = 50\%$ give us a roof aspect ratio of about 2. A caldera diameter of 1 km gives a depth of about 2 km for the chamber, which is in good agreement with the location of the pre-eruptive inflation source at 300 masl as given by Peltier et al. (2007).

The Dolomieu caldera, with a diameter of 870 × 1030 m, a volume of 0.09 $km^3$ and a depth of 340 m is smaller than the other recently formed calderas. The Fernandina caldera (Galapagos archipelago), formed in 1968, is much larger, with a diameter of about 5.5 km and a volume of 1 to 2 $km^3$ (Simkin and Howard, 1970; Filson et al., 1973).

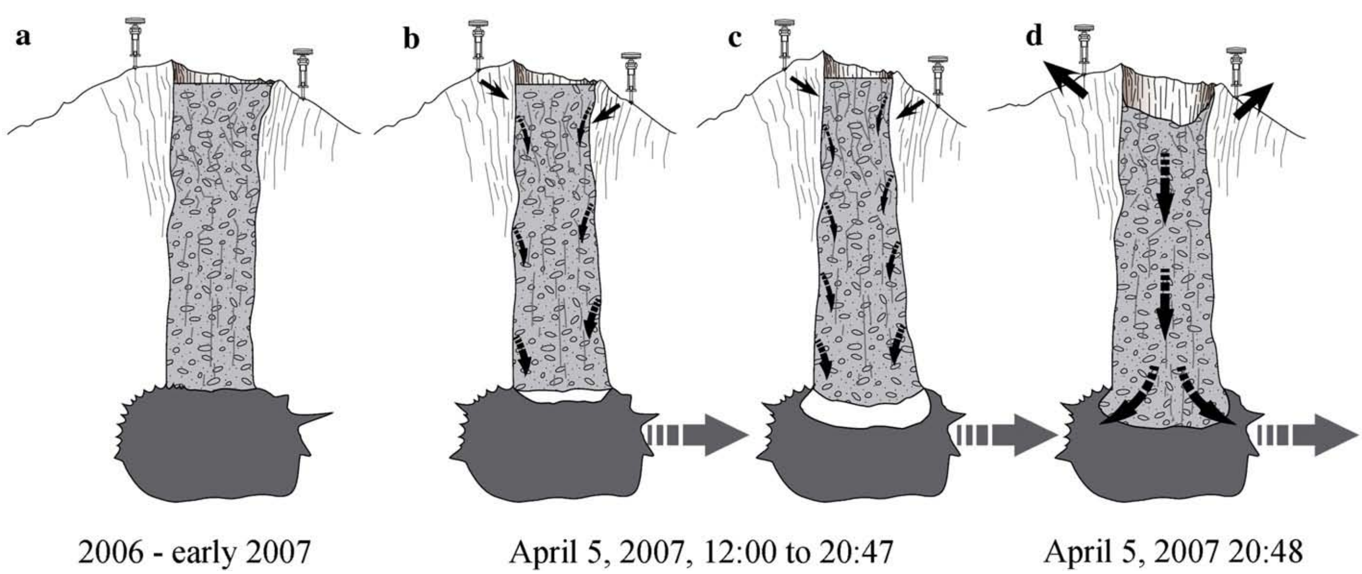


**Fig. 14.** Scenario of the Dolomieu caldera collapse. a) The rock column beneath Dolomieu crater is supported due to the pressure in the magma chamber. b–c) Rapid lateral withdraw of magma from the magma chamber lowers the pressure in the latter and deflate the summit of Piton de la Fournaise. d) The rock column collapses into the magma chamber relaxing the Piton de la Fournaise massif.

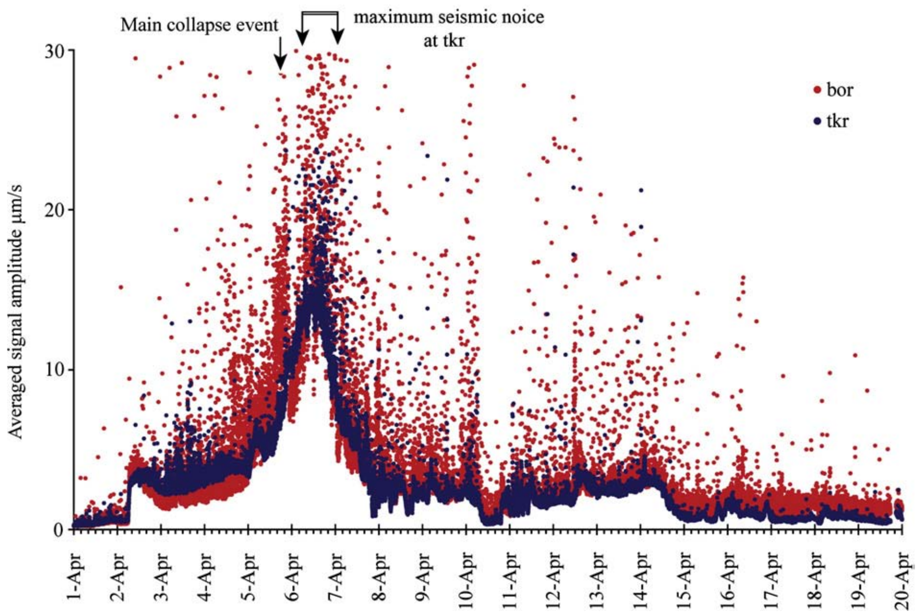


**Fig. 15.** Seismicity related to the April 2007 eruption and the Dolomieu collapse. Averaged seismic noise amplitude recorded at two seismic stations during the April 2007 eruption: bor (red points) and tkr (dark blue points). The bor station is a summit station, close to the Dolomieu crater and the recorded seismicity represents best the Dolomieu collapse, while the tkr seismic station is situated about 10 km away from the summit and close to the eruption site and represents mainly the eruption tremor. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The Miyakejima caldera, formed in 2000 in Japon, has a diameter of 1.6 km, a volume of 0.67 km$^3$, and a depth of 500 m (Geshi et al., 2002; Furuya et al., 2003). However the main Dolomieu collapse occurred within less than 24 h, while the Fernandina collapse lasted several days (Simkin and Howard, 1970) and the Miyakejima collapse started on July 8, 2000 and continued until mid-August (Hasegawa et al., 2001). According to Acocella (2007), Miyakejima and Dolomieu calderas can both be classified as stage 4 calderas, with a diameter over subsidence ratio <14, even though they represent the low end members of this group.

The question is, whether the erupted and collapsed volumes can be compared. At Fernandina, a small eruption preceded the collapse. However the volume of the collapse was about one order of magnitude larger than the erupted volume + the volume of collapse related ash deposits and no evidence of any associated submarine volcanism exist (Simkin and Howard, 1970). For that reason Simkin and Howard (1970) proposed a possible lateral dike intrusion within the underlying crust. The Miyakejima collapse, which started on July 8, 2000, was preceded by a submarine eruption on June 27 and by contemporary phreatic and phreatomagmatic eruptions on July 8, 14 and 15. From August 10 to August 29, 2000, intermittent explosive eruptions accompanied the ongoing collapse (Nakada et al., 2001). The total volume of deposits was only 0.017 km$^3$, (Hasegawa et al., 2001), which represent 3% of the collapsed volume. The latter does not include any sub-aqua erupted material. It is however unlikely that this volume represent more than 0.5 km$^3$. Therefore Geshi et al. (2002) proposed a large lateral intrusion. Thus in both cases the direct comparison between erupted and collapsed volume is not possible.

The present situation at PdF is different. The Dolomieu collapse represents a volume of $90 \times 10^6$ m$^3$. The mean flow rate of the eruption is about 50 m$^3$ s$^{-1}$. Assuming that the lava output at PdF eruptions is an approximated function of the tremor source amplitude (Battaglia et al., 2005), we can estimate that the output rate from April 2 to April 14 was about 2 times higher than the mean value (Fig. 15) and about 6 times higher from April 5 at 12:00 to April 7 12:00. Thus we get a total of $28 \times 10^6$ m$^3$ from April 2 to April 5, 12:00 and $52 \times 10^6$ m$^3$ from April 5, 12:00 to April 7, 12:00. Taking into account a 7 km long and 1000 m high dike with a thickness of about 1 m (which is a typical value for dikes at PdF) we obtain further $10 \times 10^6$ m$^3$. In addition, PALSAR Interferograms show co-eruptive movements on the eastern Piton de la Fournaise flank, which could correspond to a $10 \times 10^6$ m$^3$ sill (Okuyama, 2008). Adding all these volumes together suggest an extruded or hidden lava volume of the order of $100 \times 10^6$ m$^3$ at the time of the collapse. If we take into account a porosity of the emitted lava of 20 to 30% (Keszthelyi and Pieri, 1993; Thordarson, 1995; Malengreau et al., 2000) we get a dense rock equivalent volume of the erupted magma of about $80 \times 10^6$ m$^3$, which coincides reasonably well with the collapsed volume.

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