Structures and evolution of the plumbing system of Piton de la Fournaise volcano inferred from clustering of 2007 eruptive cycle seismicity

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Abstract. The analysis of the seismic activity associated to the eruptions of 2007, which led to the collapse of the Dolomieu crater on April 5, reveals the link between the seismicity and the magma transfers at Piton de la Fournaise. Three eruptive phases occurred on February 18, March 30 and April 2, 2007, illustrating the three types of eruption defined for the current Piton de la Fournaise activity, respectively at summit, on the South-East flank and lateral. The avril 2 eruption took place 8 km away from the central cone on the South-east rift-zone of le Piton de la Fournaise volcano. We use cross-correlation of seismic waveforms and clustering to improve the earthquake locations and determine the best-constrained focal mechanisms. The pre-eruptive seismicity of February and March eruptions forms time extended clusters and reactivates several clusters found preceding other distal eruptions of the 2000-

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2008 period. The seismicity preceding the Dolomieu collapse takes place in numerous, but time limited, clusters. These results show the preparation of the April eruption two months earlier, and the collapse of Dolomieu crater which is associated with a specific seismicity. From April 1 to April 5, Compensated Linear Vector Dipole (CLVD) occurred between 0.8 and 0 km above sea level, associated with normal faults and the collapse of the superficial part of the Dolomieu crater. After the Dolomieu collapse, the conjugate faulting of the CLVD zone has opened the 0 km to -0.5 km level corresponding to the shallower magma chamber. This opening induced the propagation of a depressurization front along a narrow conduit from sea level toward depth and triggers a migration of the seismicity from -0.5 km to -8 km. A global view of the results, given by the slips extracted from source mechanism determination and the relative relocations underlines the stress field induced by the intrusion. Our results are consistent with the beginning of the February intrusion towards the April 2007 eruption site. The collapsed column above the shallow magma chamber corresponds to the CLVD generator is the cause of the Dolomieu caldera.

1. Introduction

Caldera collapses due to lateral eruptions are typical of basaltic volcanoes and some historical examples are well-documented for the 1924 eruption at Kilauea, Hawaii [*Dvorak*, 1992], the 1968 eruption at Fernandina, Galapagos [*Simkin and Howard*, 1970], the 1975-1977 eruption at Tolbachik, Kamchatcka [*Fedotov et al.*, 1980] and the 2000 eruption at Miyakejima volcano, Japan [*Geshi et al.*, 2002]. On the other hand, caldera formation may also occur in subduction context. *Hildreth and Fierstein* [2000] described the summit collapse that occured during the 1912 lateral eruption on the Katmai volcano. They notice that the seismicity associated with the collapse released 250 times more seismic energy than the 1991 Pinatubo caldera events (Philippine) and may be due to the absence of pre-existing caldera fault at Mount Katmai. Smaller collapse structures also form at Piton de la Fournaise such as the 1986 collapse of 80 m deep pit crater ending the lateral of the 1985-1986 eruptive cycle [*Lenat et al.*, 1989]. *Hirn et al.* [1991] highlighted the pre-collapse seismicity as dilatation Compensated Linear Vector Dipole (D-CLVD). They interpreted D-CLVD as sudden increase of fluid volume in vertical fluid filled cracks linked with underlying magma storage. This hypothesis is also supported by *Aki* [1984]; *Julian and Sipkin* [1985]; *Chouet and Julian* [1985] and *Kanamori et al.* [1993]. *Hirn et al.* [1991] also observed long period seismic events during the subsidence of the pit-crater presenting similar features with the seismic events associated with the Fernandina caldera collapse [*Filson et al.*, 1973]. Both authors considered these events as the exitation of the resonance of empty cavities resulting of magma withdrawal. At the Miyakejima volcano, *Uhira et al.* [2005] relocated the hypocenters of the pre-collapse lateral migration and determined strike-slip and oblique focal mechanism. *Kikuchi et al.* [2001] studied the syn-collapse seismicity and observed a very long period seismic swarm under the summit. *Kumagai et al.* [2001] perform inversion and modeling of the syn-collapse seismicity and proposed a model in which a vertical piston of solid materials in the conduit is intermittently sucked into the magma chamber by lateral magma ouflow. Independently, *Geshi et al.* [2002] detailed the caldera structure and the nature of the eruptive materials and suggest that subsidence was caused by the upward migration of a steam-filled cavity. The results of seismic surveys of caldera collapses suggested the crushing of magma storage zones. The results of structural studies are hardly compatible with the seismic models. Most seismic studies focus on the syn-collapse seismic events and the birth, the development and the evolution of collapsing structures have not been performed.

Here we study the 2007 eruptions of Piton de la Fournaise volcano, Réunion, and the April 2007 collapse using the seismic data of the Piton de la Fournaise Observatory. The main objective of our study is to characterize the structures, their origin and the mechanism of the summit collapse of Piton de la Fournaise. To propose a comprehensive view of the seismicty, we use waveforms cross-correlation technique to define the pre-existing and newborn seismic structures. The cross-correlation has shown great success in various tectonic environments as for the Soufriere Hills volcano, Montserrat [*Rowe et al.*, 2004] and for Piton de la Fournaise volcano [*Battaglia et al.*, 2005]. The automated correlation and clustering methods, reduce picking inconsistencies and improve the earthquake localizations for determining best-constrained focal mechanisms. Relocation and determination results are then used for co-seismic slip extraction and stress field study.

2. Volcanological settings and chronology

Piton de la Fournaise is one of the world's most active basaltic shield volcanoes originating from La Réunion hotspot [*Courtillot et al.*, 1986; *Lénat and Bachèlery*, 1990]. Its activity is mostly concentrated at the top of the 400 m high cone that built in the 4.5 ky-old Enclos Fouqué caldera [figure 1 ; *Bachèlery*, 1981]. Eruptions occur, less frequently, outside the caldera along the NE and SE rift zones, the last occurrence being the 1986 eruption during which the summit experienced a pit crater collapse [*Lenat et al.*, 1989; *Hirn et al.*, 1991]. Considering the location of the eruptive sites, three different types of eruptions have been defined [*Peltier et al.*, 2008a]: (i) summit eruptions start and remain in the summit collapsed structure; (ii) proximal eruptions begin at or close to the summit and subsequently propagate downhill; (iii) distal eruptions arise on the volcano flank, several kilometers away from the summit. The occurrence of coalescent collapse structures at the summit of the active cone suggests that the eruptive activity was contemporaneous with recurrent collapse events [*Lénat and Bachèlery*, 1990; *Carter et al.*, 2007]. The two most recent structures correspond to Bory and Dolomieu (figure 1).

In 1998, the eruptive activity of Piton de la Fournaise resumed after a lull of 6 years. Since then, the volcano experienced two successive eruptive patterns, which show differences in terms of seismicity and deformation of the edifice [*Michon et al.*, 2007; *Peltier et al.*, 2009]. Before 2000, eruptions were preceded by a few days of low-level seismicity. Once the eruption started, volcano-tectonic (VT) events seldom occurred and the tremor was progressively decreasing until its disappearance. Since 2000, the volcano underwent a significant pre-eruptive inflation before each eruption coeval with an increasing seismicity. The seismicity was decreasing after the onset of the eruptive phase and next rapidly increasing. This second phase was particularly important during distal eruptions [*Michon et al.*, 2007]. Since 2000, the eruptive activity was also characterized by the occurrence of eruptive cycles starting with summit eruptions and ending with distal ones [*Peltier et al.*, 2008a]. The August 2006 summit eruption was the beginning of the 2006-2007 eruptive cycle of Piton de la Fournaise volcano [*Peltier et al.*, 2009].

Three eruptive phases occurred in 2007, illustrating the three types of the current Piton de la Fournaise eruptions [see table 1 and *Peltier et al.*, 2009]. February 18 was a summit eruption, preceded by a 27 minutes long seismic crisis located above sea level, under the summit of Piton de la Fournaise. This eruption lasted 9 hours and took place along an east west fissure across the Dolomieu crater. The next eruption occurred on March 30 after a seismic crisis of 144 minutes. The volcano-tectonic (VT) earthquake's foci of the seismic crisis first shifted towards the north-east part of the Enclos Fouqué and then towards the south-east. March 30 was a 10 hours long proximal eruption, at elevation of 1900 m, on the south-east flank of the central cone. Between March 31 and April 2, a seismic crisis occurred, with several thousands of VT earthquakes under the summit and under the eastern slope of Le Piton de la Fournaise. On April 2, at 6:00, a 27 days long distal eruption started on the south-east rift-zone of PdF, 8 km away from the summit, at altitude of about 600 m in the Enclos Fouqué. Dolomieu crater collapsed on April 5 and 6, during a paroxysmal phase of activity. The collapse came with cycles of increasing seismic noise. The first of them ended with a 3.2 duration magnitude earthquake [on April 5, at 20:48, *Staudacher et al.*, 2008]). *Michon et al.* [2007] and *Staudacher et al.* [2008]

described these cycles and showed the link between the cycles of seismic noise, the ground deformations and the tremor step by step amplification at the locus of the eruption. They observed that the cycles corresponded to the Dolomieu crater collapse in a fast succession of subsidence events. The April 2 2007 eruption of the Piton de la Fournaise volcano produced 180.10^6 m^3 of lava [the biggest volume known for the historical period, 90.10^6 m^3 on land, *Staudacher et al.*, 2008], [and 90.10^6 m^3 in the ocean, *Saint-Ange*, 2009] and lead to the Dolomieu crater collapsed to form a depression with a depth of 330 m and a volume of around 110.10^6 m^3 [*Staudacher et al.*, 2008; *Urai et al.*, 2007]. This pit-crater formation is one of the best instrumented since the Miyakejima summit crater collapse in 2000 [*Geshi et al.*, 2002; *Michon et al.*, 2007].

3. Data acquisition

The Volcanological Observatory of Piton de la Fournaise (OVPF) seismological network is composed of 25 vertical or 3 components, 1 Hz or broadband seismometers. As shown in figure 1 the network consists of concentric circles around the summit of the volcano. Data are transmitted by radio to the observatory and continuously recorded and analyzed by ***Earthworm*** program [*Johnson*, 1995] that generates data file whenever an event is detected. From January 2007 to the end of October 2007, we recorded over about 4250 triggers and 714 events have been localized manually with an average of 12 picked phases per event. ***Earthworm*** module is set to detect the smallest events and a first task was to eliminate all spurious events such as thunder, rock falls or helicopters triggering. In order to do so, considering only the vertical component of ***bor*** station (figure 1), we computed the cross-correlation coefficient of the 714 located events with the set of 4250 triggered events. ***bor*** station is one of the first digital seismometer installed on the summit of the volcano and is well situated to record the smallest events. We then selected all the events that gave a cross-correlation coefficient greater than 0.5 and recover a set of 1866 events that added to our first selection, forms the starting dataset of our study.

4. Data processing

4.1. Clustering

We developed an automatic cross-correlation and clustering algorithm with ***Matlab®*** (R14SP1, The MathWorks, .Inc, Natick, Massachusetts) for measuring waveform similarity. We consider the vertical component of one station at a time and compute the cross-correlation coefficient between all possible pairs of events. Two pairs of events, A-B and C-B, are merged in one family if they involve a common event, B, and if they reach the cross-correlation coefficient threeshold of 0.85. In each family, we choose for master the best-constrained earthquake from hand-picked localization. The localizations are computed from a modified version of ***Hypo 71*** [*Lee and Lahr*, 1975] by *Nercessian et al.* [1996] taking the station elevation into account. A visual checkout step is required to remove glitch-type clusters. To strengthen our results and to identify the maximum number of clusters, we applied this clustering method to 6 stations (triangles in figure 1).

1. The first one, ***bor***, has the best signal to noise ratio on the main part of seismicity.
2. ***TCR*** is located at the base of le Piton de la Fournaise summit cone.
3. ***fer*** is the station with the best signal to noise ratio located on the east side of PdF.
4. ***NTR*** is a station located on the southern cliff of the Enclos Fouqué caldera.
5. ***PER*** is a station located outside of Enclos Fouqué.

6. ***RMR*** is located in the Piton des Neiges area (in the northern part of the island, figure **??**) and is often the nearest station to the deep seismicity occurring under La Réunion Island.

Finally 374 clusters have been selected to form the cluster dataset. Considering each cluster, the pick times of the master event are applied to each slave events using the alignement of waveforms at the maximum of the cross-correlation function (three examples are shown in figure 2). The clusters are used to produce a cross-correlation catalog for ***HypoDD***, that contains, for each clustered event, the differential travel times between the event and its master for each picked phase [*Waldhauser and Ellsworth*, 2000]. From a dataset of 2580 triggered records our cross-correlation process allowed us to recover 1625 events for relocation.

4.2. Relative relocation and source determination

The set of clusters has been relocated using ***hypoDD*** program [*Waldhauser and Ellsworth*, 2000]. Following *Waldhauser and Ellsworth* [2000], our cross-correlation catalog minimizes the number of earthquake pairs. ***hypoDD*** used a differential travel time catalog to form and solve double-difference equation systems. The input velocity ratio is the same as in other studies on Piton de la Fournaise [*Hirn et al.*, 1991; *Nercessian et al.*, 1996; *Battaglia et al.*, 2005]. The chosen LSQR mode [*Paige and Saunders*, 1982] can efficiently solve a large system but errors reported by LSQR are under estimated [*Waldhauser and Ellsworth*, 2000]. Using this approach, 633 out of 1625 events were relocated in the LSQR mode, and 461 events were relocated in the SVD mode to assess independently errors reported by LSQR. ***hypoDD*** input consisted in 35476 P and 4079 S cross correlated differential travel times. All the relocated events have more than 8 differential travel times similarities. In average, 12 phases per event and one or more picked time on S waves have been considered in the relocation and the 633 relocated events have an averaged rms of 0.041 s. Composite focal mechanisms were determined using ***FPFIT*** program [*Reasenberg and Oppenheimer*, 1985] for each cluster considering a set of 78 P phases polarities in average.

5. Results

5.1. Correlation highlights earthquake organization

The representation of the time evolution of the clusters shows the activity of each seismic cluster. Figures 3A and B display the event occurrence as function of time and according to cluster belonging. The pre eruptive seismicity of April distal eruption reactivates several clusters that can be found in other preceeding distal eruptions of the 2000-2008 time period (figure 3A). Figure 3B shows the results obtained for the year 2007. Clusters are arbitrary classified in 6 types depending on their lifetime. Yellow clusters occurred only in the pre eruptive period of February. Green clusters occurred only during March pre eruptive period. Related to these two periods, cyan clusters represent earthquakes that preceded both February 18 and March 30 eruptions. The magenta clusters are associated with the pre-eruptive activity of the April eruption (from March 31 to April 2) and with pre collapse seismicity. The later contain (in magenta) the largest number of clusters that contain also the largest number of events. Between April 2 and the collapse, the lifetime of these clusters is limited to a few days. After the collapse, the cluster lifetime tends to increase until the end of eruption. Figure 3A suggests that the structures involved during the pre-eruptive crisis of February, March and April correspond to main structures that are reactivated since June 2000. On the other hand, the seismicity prior to the Dolomieu crater collapse corresponds to numerous and large clusters that have a very short lifetime of about 5 days. The global phenomenon has thus been prepared since 2000, but the Dolomieu collapse has its own seismic signature.

Figures 4A and 4B display respectively map and cross sections of earthquakes locations before and after the relocation using the cross-correlation catalog. Overall, in figure 4B, hypocenters show smaller error bars and smaller spatial dispersion than in figure 4A. Figure 4B shows also narrower seismic zones and highligths four levels of seismicity. Superficial seismicity occurs above 0.8 km asl (above sea level). Densest located seismicity takes place between 0.8 km and 0 km asl and most of the earthquakes during pre-eruptive periods and seismic crisis occurs in this level. This level also involves the largest magnitude earthquakes. A third level between 0 and -0.5 km is less active (active only during and after April). The deeper level on figure 4B and on figure 7E extends vertically from -3 km to -8 km, with a denser stage between -4.5 km and -5 km. Other seismic clusters have been relocated under the eastern flank of le Piton de la Fournaise around -2 km, making up a fifth isolated level.

5.2. Source mechanisms analysis

The source mechanisms of 154 clusters have been determined as pure double couple. Most of the double couple solutions correspond to earthquakes occuring between February and March 2007. Strike, dip and rake have average uncertainties of 4.8°, 4.0° and 6.6° respectively. Since we do not consider the heterogeneity of elastic properties, in the description of the results, we shall consider the relative position of clusters rather than the absolute location of each source. Examples of source mechanisms are shown in figure

5. We identified pure double couple sources, oriented as strike slip (figure 5A) and normal fault, but also Compensated Linear Vector Dipole clusters [CLVD, *Knopoff and Randall*, 1970], with either a vertical dilatation (D-CLVD, 5B) or a vertical compression (C-CLVD, 5C) axis. These events respectively show an isolated phase of compression and dilatation on ***bor*** and ***dsr*** stations. The focal mechanism solutions are shown with colors according to those of the clusters in figure 6 and 7.

Figure 6A shows the cyan clusters of figure 3A activated before the February and March eruptions. From these 26 clusters, 5 clusters have been identified as D-CLVD, 6 clusters have been determined as strike slip faults, and 11 clusters have been determined as normal faults. Hypocenters are distributed along two branches from 0.3 to 0.8 km, below the northern and the southern part of the summit. D-CLVD and strike-slips take place between 0.3 and 0.6 km, below the southern part of the summit. The strike-slips are all oriented as sub-vertical faults showing varying directions. Normal faults occurred between 0.3 and 0.8 km, below the northern part of the summit. This seismicity underlines clearly the northern scarp of Bory crater with normal faulting and the southern part of the summit with strike slip faulting and dilatation CLVDs. The association of normal fault and strike-slip must be induced by a common stress field existing during the preparation of the two eruptions preceding the April distal eruption.

Figure 6B shows the 17 clusters that cover the 15 days preceeding the March eruption. In the southern part, 10 clusters show strike-slip faulting, with similar orientation. They take place in the southern branch described before, forming a dense seismic zone around 0.5 km. In the same locus, five clusters are identified as D-CLVDs. More, the last cluster of March is identified as C-CLVD and is relocated at 0.3 km asl. The association of oriented strike-slips and D-CLVDs below the southern part of the summit is the main specificity of the March eruption precursors.

From March 31 to April 5, before the collapse of Dolomieu crater on April 5, at 20h50, the summit part of Piton de la Fournaise shows a clear seismic signature. Figure 6C shows the short life-time clusters of figure 3A that preceded the collapse of Dolomieu crater. The whole seismic activity for the five days before the collapse has been relocated under the southern part of the summit, between sea level and 0.8 km asl. Taking into account the localization and the polarity phase, 24 clusters of C-CLVDs show a compression axis inclined 80° toward the south-west. In the same time span, we found 7 clusters determined as normal faulting relocated in the same area than March strike-slip, around 0.3 asl. The source determination of all normal mechanisms gives the same nodal plans with a north-south strike and a west dip. Observation of the results suggests that normal faulting is linked to the CLVD generator. The comparison of figure 6B with figure 6C underlines that the strike-slip fault and the D-CLVD of February and March leave place before the collapse to the clusters of C-CLVD. From April 1 to April 2, earthquakes also took place at -2 km under the eastern flank of Le Piton de la Fournaise and seems to be due to the return to an equilibrium state of the eastern flank during the final injection toward the eruption locus. These earthquakes have been determined as SW-NE normal mechanisms not shown here.

In figure 7D, two yellow clusters span April 5 - June 5 time period. They are located under the southern part of the summit, between 0.3 to 0 km, in the same zone as the former CLVD generator and strike-slip area. They show normal faulting with the same orientation that the one observed just before the collapse. Normal faulting takes place also at sea level (purple clusters) with east-west faults. A dense cluster of undeterminable earthquakes has been relocated under the south-western part of Bory crater, around sea level. A fourth cluster denser than the preceding one, starts at -0.5 km, between Bory and Dolomieu craters. Hypocenters of this cluster can not be determined as a pure double couple or a CLVD. An aseismic zone between 0 and 0.5 km bsl could be defined in cross section views and the three clusters just described are distributed around this zone. Finally, an U-shaped ring of superficial normal faults underlines the Bory crater, from 1 km asl to 1.5 km asl.

5.3. Co-seismic slips

For each cluster, we noticed that the hypocenter relocations are usually lying along one of the nodal planes, which was chosen to define the fault. We then measured the co-seismic slip orientation along this plane. Their representation from February to March 31 allows to get a general view of the stress field before the collapse of the Dolomieu crater. Figure 8 shows co-seismic slips in the northern parts directed towards the center of the volcano. While, in the southern parts, the co-seismic slips are oriented outward the center of the volcano. Cross sections show two different kinds of slips. In the south-eastern part, co-seismic slips dip 20° above the horizontal. In the three other parts, co-seismic slips dip 60° below the horizontal. North-South cross section also shows at 0.8 km that a small part of the centripetal and centrifugal slips are mixed in the transition between north and south.

The co-seismic slips in the south-eastern part are extracted from the strike-slips described before. They indicate the existence of an uprising source below the southern part of the summit. The growth of this source started in February (and give the diversity of strike-slips of the common clusters to February and March, figure 6A, section 5.2). This stress field perturbation evolves at the end of March and leads to the aligned strike-slips of the March cluster, figure 6B, section 5.2. In the northern part, the slip dips of 60° may correspond to a subvertical stress field, suggesting the gravity. To summarize, co-seismic slips show only one stress field perturbation below the southern part of the summit. It leads to the up-rising of the south-eastern side toward the S-SE and to the subsidence of the northern quarters. This perturbation is initiated in February and developed until the end of March.

6. Discusion

Figure 9 represents the scheme suggested by our results. The initial state of figure 9 is composed of a magma chamber with a top located around sea level and a north south radial fault from sea level to 0.8 km, above the southern part of the magma chamber. *Nercessian et al.* [1996]; *Peltier et al.* [2005, 2007] and *Peltier et al.* [2008b] developed the hypothesis of a shallow magma chamber feeding the eruptions of Piton de la Fournaise. These authors localized it below the Dolomieu crater, around sea level. Our results show an aseismic zone from -0.5 km to 0 km, slightly shifted toward the west of the Dolomieu crater. Above the magma chamber, we recognized strike slip mechanisms along a network of north-south radial faults. Such radial fault has been highligthed by the structural study of the summit cracks by *Bachèlery* [1981]. Radial cracks take place in the southern part of the summit and in the northern part. All around the two summit craters, *Bachèlery* [1981] describes several networks of concentric faults. The seismic radial faults observed in our study could be linked with the summit radial cracks in the southern part of the summit. These radial faults are the preferential planes of rupture, and were created before the 2007 eruptions.

6.1. Strike-slips mechanisms

Our clustering results permit to highligth the role of the strike slip mechanisms. They are associated with the preparation of the February and March eruptions. They form a network of radial faults rising from sea level to 0.8 km and they show oblique focal mechanism with a uprising component toward south east. We propose that this kind of radial fault accomodate the pre-eruptive inflation of the magma chamber with strike slip (figure ??B). The strike slip open a vertical volume along the asperity of the radial fault. The opened conduit could be filled by magma, building some magma funnel that can feed the February and March eruptions. The inflation of a sea level magma chamber before March eruption has been studied by *Peltier et al.* [2008b] and *Augier* [2008]. The pre-eruptive deformations and the seismic crisis's deformations of the February and March march eruptions [*Peltier*, 2007] clearly show a relative uprising of the southern part of the summit, which is in good agreement with the relocation of our oblique strike slip. More, the intrusion of magma along the radial fault can be proposed as in *Roman* [2005] calculation of Coulomb stress change shows that dyke injection triggers strike slip faulting along pre-existing faults around the conduit. At Miyakejima volcano, during the 2000 eruption, strike-slip mechanisms in the context of volcano-radial compression axis have been recognized to be associated to lateral intrusion [*Uhira et al.*, 2005]. Considering our results and previous studies, the strike slip column could be the locus of seismic accomodation of the magma chamber inflation, and a preferential path of intrusion. The occurrence of the same strike slip faults during February and then during March clearly shows that both dyke intrusions started from the same structure and origin.

6.2. The sill hypothesis

The long lifetime strike slip clusters come with normal faulting clusters. The strike slip faults could be associated with intrusions, but the normal faults must be interpreted with another phenomenon. The normal faults form a second column, from sea level to 0.8 km above the northern part of the sea level magma chamber. They could be linked with the magma chamber, and show that the uprising of the southern part of its roof toward the south east is associated with the subsidence of the northern part of its roof. Such subsidence does not appear in the specific clusters of the preparation of the March eruption, and is not associated with the magma intrusions in the strike slip column. We suggest that the normal faulting indiced a major phenomenon started in February: the intrusion of a sill from the southern part of the magma chamber toward the April 2 eruption site. This assumption has not been highligthed by previous studies. GPS displacements [*Peltier et al.*, 2008b] and radar interferometry [*Augier*, 2008] have both highlighted the March 30 intrusion but did not constrained the intrusion toward April 2 eruption site. In fact, the deformation data are recorded preferentially around the summit, they are influenced by superficial structure, and the amplitudes of the deformations around the central cone of Piton de la Fournaise are not easily interpretable. The deformation data can not disprove the sill hypothesis and the stress field extracted from co-seismic slips is consistent with this idea. We do not expect to constrain the path or velocity of the distal intrusion with seismicity but we show that detailed study of summit seismicity is helpful for the characterization of a distal intrusion.

6.3. Strike-slip mechanisms and D-CLVD

The strike slip column is the locus, in March, of D-CLVD activity (figure 9B). CLVD mechanisms have been repeatedly observed in volcanic areas and have been interpreted from theory as the result of fluid injection [*Aki*, 1984; *Julian and Sipkin*, 1985; *Chouet and Julian*, 1985; *Kanamori et al.*, 1993]. According to *Hirn et al.* [1991] we assume that the D-CLVDs of March are due to rapid volume increase in a vertical fluid filled crack. Regarding the very similar relocation of strike slip and D-CLVD, we propose that there is a link between the strike-slips and the D-CLVDs of March. The filling of the radial fault aspirities during the inflation of the underlying magma chamber shall lead to the pressurization of the magma funnel, building a D-CLVD generator. Considering the dimensions of the D-CLVD column, we obtain a aproximated volum of $1.2.10^7$ m^3 for the the magma funnel area. We can not distinguish from this volume, the February associated part from March one. Each D-CLVD indicate a step of rapid pressurization of the D-CLVD generator which grow all along March month.

6.4. The C-CLVD crisis

The CLVD generator reached a critical state when, from April 1 to 5, an intense seismic crisis with C-CLVD was recorded (figure 9C). 315 earthquakes from this kind of seismicity have been identified as C-CLVD from April 1 to 5. They take place along a column rising from sea level to 0.8 km asl, just above an aseismic zone surrounded by several undeterminable clusters from sea level to -0.5 km. Our study is limited by the lack of tensor inversion which could constrain the volumetric component of CLVD. Possible research about this subject will be complicated by the heterogeneity of the volcano physical properties. In fact, at very short periods, especially at small hypocentral distance, the influence of lateral heterogeneity's is critical: a 1D model is a very bad approximation of the real medium and does not accurate enough to provide a good agreement between observed and synthetic seismograms. Getting a 3D velocity model on the basis of Green function computation or extracted from seismic noise interferometry results could provide important improvement. We assume that each C-CLVDs from April 1 to April 5 are due to a rapid volume decrease in a vertical fluid filled crack. At this moment, the CLVD generators might be too much developed to resist to the lithostatic loading during the underlying magma chamber draining off started on April 2. The chronology of C-CLVD's cluster suggests that C-CLVDs are precusors of the Dolomieu collapse. The waveform clusters of this crisis are very intense and their lifetime are very short suggesting a network of CLVD sources activated one after others. The stress field must have been perturbated by a fast structural evolution during the crisis that triggered the Dolomieu collapse.

6.5. The shallow magma chamber and its link to depth

Relocation and source determination results support the existence of a shallow magma chamber, and constrain its roof at sea level. For that, three observations of our results are considered. (i) the existence of an aseismic zone between 0 and -0.5 km, (ii) above this zone, the post-collapse normal faulting column and the collapse of the CLVD generator, (iii) below, a seismic source migration from -0.5 to -8 km, from April 12 to May 8. We propose that the draining off of a magma chamber between sea level and -0.5 km results in the collapse of vertical fluid filled cracks. When the collapse reached the surface, and during the crumbling of the collapsed fluid filled cracks, the magma chamber could have been suddenly depressurized. Finally, the depressurization front propagates from the sea level magma chamber toward depth, along a narrow path. The vertical conduit from depth to the sea level magma chamber has been proposed by *Pinel and Jaupart* [2003] and imaged by *Battaglia et al.* [2005] from -5 km. Recently, the passive tomographic model of Piton de la Fournaise proposed by *Prôno et al.* [2008] clearly showed the presence of a magma chamber around -1 km and suggests a network of magma pocket in a intrusive complex from sea level to 1 km. These authors propose the existence of a seismic interface at sea level without sea level magma chamber. Above sea level, this model is in agreement with the first model of the Piton de la Fournaise plumbing system proposed by *Lénat and Bachèlery* [1990] and could be consistent with our results. But we can not fit with the tomographic image of *Prôno et al.* [2008] of a magma chamber around -1 km. An open conduit shall make the link between the sea level chamber and the 1.2 km bsl chamber.

7. Conclusion

Our results show that the pre eruptive seismicity of the April 2007 distal eruption of Piton de la Fournaise volcano reactivate several clusters that were also active before other distal eruptions of the 2000-2006 period. There is no direct reference in literature about this subject. For the first time, our results clearly highlight similarities in the seismicity from preparation of eruptions during 2000, 2002, 2004, 2005 and 2007 (figure 3). We do not show here the sources relocation and determination of clustered earthquakes of 2008 and between 2000 and 2006. This seismicity should be investigated to obtain information about the common seismicity preceding each type of eruption. Future researches about this subject will give help for the monitoring of eruption type at Piton de la Fournaise volcano. This study highlights the long lifetime cluster of strike-slip faults, associated with the growing of CLVD generators. The CLVD generators grow during the intrusions supplying the summit and proximal eruptions and have a structure consistent with the stress field induced by the preparation of distal intrusion. Finally, it reached an unstable state in April 2007, and became the source of the caldera collapse and of the opening of bellowing magma storage level.

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