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How summit calderas collapse on basaltic volcanoes: New insights from the April 2007 caldera collapse of Piton de la Fournaise volcano

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ABSTRACT

In April 2007, Piton de la Fournaise volcano experienced a caldera collapse during its largest historical eruption. We present here a structural analysis both of the caldera and the surrounding area, and precise GPS data recorded with a dense GPS network specifically dedicated to the analysis of deformation related to the summit collapse structures. Despite a collapse of more than 300 m in the central zone, the geometry of the new caldera is similar in map view to that of the pre-existing collapsed structure, which was formed from the coalescence of several pit craters. The caldera shows an asymmetric inner geometry with sub-vertical walls in the NW quadrant and steep scarps composed of inward tilted blocks in the southern half. The presence of preserved polished surfaces on the lower part of the sub-vertical scarp indicates that it corresponds to the caldera north-western ring fault. The April 2007 caldera collapse led to the development and the reactivation of concentric fractures on the caldera rim, mostly along the southern limit of the caldera. GPS data show that fractures result from radial extensional stresses that are restricted within the first tens of meters of the caldera edge. GPS data also reveal that the caldera collapse was coeval with a centripetal deflation, whose magnitude is largest along the southern half of the caldera. The displacements recorded by GPS result from both a general deflation, due to magma withdrawal from Piton de la Fournaise's summit magma chamber, and additional local effects related to the caldera collapse. Comparison of the caldera collapses at Piton de la Fournaise, Miyakejima and Fernandina reveals striking similarities, with cyclic seismic signals accompanying small-scale deflation–inflation cycles. This strongly suggests a common mode of collapse. Hence, we propose a unifying model of caldera collapse in basaltic setting, in which the inward deflation due to magma withdrawal from the magma chamber prevents the collapse of the caldera roof until the gravitational stress acting on the rock column above the magma chamber exceeds the shear strength along pre-existing ring faults. The downward displacement stops when the pressure increase into the magma chamber is able to again sustain the rock column. The succession of (1) inward deflation that prevents the collapse, (2) collapse due to gravitational stress and (3) stopping of the downward motion is repeated many times. The frequency of the cycles is influenced by the rate of magma withdrawal and by the amount of intrusion of magma along the ring faults.

1. Introduction

Basaltic volcanoes present summit calderas, whose formation is related in most cases to lateral magma migration from a shallow magma reservoir (e.g. MacDonald, 1965). Observations of basaltic calderas worldwide, and the few recorded collapse events, show common structural characteristics and collapse mechanisms, which can be summarised as follows. First, caldera collapses are contemporaneous with a periodic seismicity underlined by either a very-long-period seismic signal (Miyakejima in 2000, Kumagai et al., 2001) or large earthquakes, i.e. between M_s 4.4 and 5.5 (Fernandina in 1968, Simkin and Howard, 1970; Filson et al., 1973). Despite differences in the type of seismic signal, their periodicity has been interpreted in the same way, i.e. an intermittent collapse of the rock column into the magma chamber (Simkin and Howard, 1970; Filson et al., 1973; Kumagai et al., 2001). Questions remain on the source of the periodicity which is interpreted as being controlled either by the constant magma outflow (Kumagai et al., 2001), by an irregular geometry of the bottom of the collapsing rock column (Filson et al., 1973) or by regular stress built up along the caldera fault, which is sporadically relieved by movement along the ring fault (Simkin and

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Howard, 1970). Second, analyses of the surface deformation have long-revealed that collapses are coeval with centripetal deflation of the edifice (Wilson, 1935; Ryan et al., 1983). Both deformations, i.e. the collapse and the inward subsidence, result from pressure decrease within the magma chamber and/or the plumbing system (Mogi, 1958; Walsh and Decker, 1971; Ito and Yoshioka, 2002). Third, collapse calderas often show peripheral concentric extensional fractures hundreds of metres from the edge of their caldera rim (Simkin and Howard, 1970; Lénat and Bachèlery, 1990; Troll et al., 2002; Acocella, 2006; Carter et al., 2007). The various authors describe an increase of extension and vertical displacements close to the caldera rim, but their interpretations differ. The changes in rim geometry are thought to result from superficial processes postdating the caldera formation (Acocella, 2006), from extensional stresses related to the centripetal subsidence (Branney, 1995), or from inflation–deflation cycles (Lénat and Bachèlery, 1990).

In April 2007, Piton de la Fournaise volcano experienced a caldera collapse during its largest historical eruption (Michon et al., 2007). We present here the summit deformation accompanying this event. We integrate a detailed analysis of both concentric fractures and intra-caldera structures and faults, with high precision GPS data from a dense network implemented surrounding the caldera. Our study benefited from an initial field and GPS campaign carried out in March 2007, a few days before the onset of the eruption and collapse. The GPS network has been reoccupied twice, in May and November 2007, in order to determine the syn-collapse and post-collapse displacements, respectively. This paper aims at determining the relationship between the concentric fractures and the collapse. It also attempts to better understand the collapse mechanism and its relation to eruption dynamics. Finally, it addresses the role of pre-existing structures in the development of a new caldera.

2. Geological setting

Piton de la Fournaise volcano is one of the world's most active volcanoes (Lénat and Bachèlery, 1987). At the edifice scale, it is characterised by two NE and SE rift zones and an E–W U-shaped caldera formed around 4.5 ka ago (Bachèlery, 1981; Fig. 1a and b). The volcanic activity is concentrated in the upper part of the U-shaped structure, the Enclos caldera, where the accumulation of volcanic products has built up a steep central cone (Michon et al., 2009-this issue). Prior to April 2007, the summit of the active cone was cut by two collapse structures: Bory in the west, which is currently inactive, and Dolomieu in the east, the location of the caldera collapse during the large April 2007 eruption (Fig. 1c). Before this collapse, the elongated shape of the pre-existing Dolomieu was the result of the coalescence of several pit craters (Lénat and Bachèlery, 1990; Carter et al., 2007). The largest of these events occurred between 1933 and 1936, during which the eastern half of Dolomieu experienced a 150 m-deep collapse (Fig. 1d; Lacroix, 1939; Bachèlery, 1981). Until 1953, the western part of Dolomieu also suffered recurrent collapses that were accompanied by progressive subsidence of the crater floor. From 1953 the lava accumulated during the frequent summit eruptions and progressively filled the collapse structure, whose outer contour remained unchanged until March 2007, despite the small pit crater collapse in 1986 (Hirn et al., 1991) and a brutal but minor subsidence in 2002 (Fig. 1d; Longpré et al., 2007). It is noteworthy that the August 2006–January 2007 summit eruption created a lava pile of 20–30 m on the Dolomieu floor, filling the crater and overtopping the eastern caldera wall (Michon et al., 2007).

In 1990, a detailed structural analysis of the summit of the active cone revealed a complex network of concentric extensional fractures concentrated around Dolomieu only (Fig. 1d; Lénat and Bachèlery, 1990). It also highlighted the asymmetric distribution of the concentric fractures around the east and west parts of Dolomieu. The eastern rim of Dolomieu was characterised by a few fractures restricted to a 50–80 m wide zone. In contrast, concentric fractures were scattered within a 200–300 m wide zone around the western half of Dolomieu. The northern limit of this fracture network coincides with a topographic break-in-slope that corresponds to the hidden boundary of a paleo-pit crater (Lénat and Bachèlery, 1990; Michon et al., 2009-this issue). South of Dolomieu, the Petit Plateau paleo-pit crater, formed around 1911 (Bachèlery, 1981), consists of an independent system of concentric fractures that delimitates the hidden collapsed structure. The age of the overall fracture system is hard to determine. However, the lack of any significant fractures south of the western fracture zones, where the lava emitted by the 1936 and 1956 eruptive fissures covers the surface (Fig. 1d), suggests that fractures in the west predate these eruptions. In the east, the similar distribution of both the limits of the 1933–1936 pit crater and the peripheral concentric fractures supports a temporal relationship between the main collapse event and the development of extension fractures close to the rim. Since 1990, the only significant change in the concentric fracture system was observed during the August 2006–January 2007 eruption, during which fractures close to the rim in the south-eastern part of Dolomieu opened of a few tens of centimetres to a few metres. These fractures accommodated the progressive inward tilting of rock panels torn apart from the rim of the collapse structure.

The April 2007 caldera collapse of Piton de la Fournaise occurred during the largest historical eruption, starting on 30th March and ended the 1st May 2007. Although the detailed evolution of the eruption has already been presented (Michon et al., 2007; Staudacher et al., 2009-this issue), we summarise below the main characteristics that allow us to interpret the origin and dynamics of the caldera collapse. On 30th March, a first eruptive fissure opened south-east of the central cone at about 1900 m above sea level (Fig. 1b). After less than 10 h, the magma emission ceased, whereas the summit seismicity remained at a very high level. The magma emission started anew on 2nd April when an eruptive fissure opened at about 600 m asl, 7 km away from the summit (Fig. 1b). The rate at which magma was discharged, which was already large, increased during 5th April contemporaneously with a summit centripetal deflation. The first summit collapse occurred on 5th April at 20:48, contemporary to a magnitude 3.2 volcano-tectonic event (Michon et al., 2007). It was immediately followed by a sudden centrifugal uplift of the caldera rim (Michon et al., 2007; Staudacher et al., 2009-this issue). The collapse also had a striking impact at the eruption site where the seismic signal increased by around 50%. Then, both the seismic signal and the summit displacements began to occur in cycles characterised by an inward deflation accompanied by an increase of the seismic signal, ending with a sharp outward uplift contemporaneous with sudden decrease of the seismicity. The cycle frequency gradually increased from 2 h to 30 min (Michon et al., 2007; Staudacher et al., 2009-this issue). A total of 38 collapse events were distinguished between 5th April, 20:48, and 7th April, 00:40. First observations of the new caldera, in the afternoon of 6th April, revealed that the 16 first collapses triggered the development of most of the summit collapse caldera (Michon et al., 2007). Disregarding continued spalling of material from the caldera wall, the final geometry of the caldera was attained on 10th April. The eruption continued at a low level until the 1st May 2007.

3. Summit deformation related to the April 2007 eruption

3.1. Structural analysis

On 6th April, the first observations indicated that the collapse was elongated along an E–W axis and concentrated in the northern part of Dolomieu (see Fig. 4b in Michon et al., 2007). It was bounded by 200–300 m-high subvertical scarps in the east, west and north, and by subsiding terraces in the south. Two annular plateaus corresponding to the pre-existing floor of Dolomieu remained in the E and SW (see Fig. 4 in Michon et al., 2007).