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Edifice growth, deformation and rift zone development in basaltic setting: Insights from Piton de la Fournaise shield volcano (Réunion Island)

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ABSTRACT

The overall morphology of basaltic volcanoes mainly depends on their eruptive activity (effusive vs. explosive), the geometry of the rift zones and the characteristics of both endogenous and exogenous growth processes. The origin of the steep geometry of the central cone of Piton de la Fournaise volcano, which is unusual for a basaltic effusive volcano, and its deformation are examined with a combination of a detailed morphological analysis, field observations, GPS data from the Piton de la Fournaise Volcano Observatory and numerical models. The new caldera walls formed during the April 2007 summit collapse reveal that the steep cone is composed of a pyroclastic core, inherited from an earlier explosive phase, overlapped by a pile of thin lava flows. This suggests that exogenous processes played a major role in the building of the steep central cone. Magma injections into the cone, which mainly occur along the N25–30 and N120 rift zones, lead to an asymmetric outward inflation concentrated in the cone's eastern half. This endogenous growth progressively tilts the southeast and east flanks of the cone, and induces the development of a dense network of flank fractures. Finally, it is proposed that intrusions along the N120 rift zone are encouraged by stresses induced by magma injections along the N25–30 rift zone.

1. Introduction

Basaltic shield volcanoes grow by the combined effect of endogenous and exogenous processes (e.g., Annen et al., 2001). Endogenous growth is mainly related to dyke intrusions, which preferentially propagate along the existing rift zones. The volcano shape consequently depends on the intensity of their activity and may vary from elongated, e.g., Karthala in Grande Comore, and Mona Loa and Kilauea in Hawaii, to sub-circular, e.g., volcanoes of Western Galapagos. Exogenous growth results from the accumulation of lava flows and pyroclastic cones (Naumann and Geist, 2000; Rowland and Garbeil, 2000). Long lava flows tend to flatten the volcano morphology, whereas short and thick ones may encourage the development of steep edifices (Naumann and Geist, 2000; Annen et al., 2001).

At Piton de la Fournaise, Réunion Island, however, the magmatic activity led to the development of a steep central cone in the Enclos caldera despite the predominance of fissure eruptions that feed fluid basaltic lava flows. Moreover the cone is almost circular whereas most of the eruptions develop along the N25–30 and N120 rift zones (Fig. 1; Michon et al., 2007a). To answer these paradoxes, Annen et al. (2001) proposed, using numerical models, that the geometry of the cone was resulting from a predominant endogenous growth with only 30% of the edifice volume directly related to short lava flows. Although the models roughly fit the current cone's geometry, the input and natural data partly disagree. First, the simulated dykes (mean thickness of 3 m) are not as thick in nature as in the models. Indeed, recent works showed that the mean dyke thickness related to the post-1997 eruptions was around 0.5–0.7 m (Fukushima, 2005; Peltier et al., 2007). Second, the model of Annen et al. (2001) simulates 10,000 dyke intrusions, 7% of them leading to an eruption. Such an intrusion/eruption ratio is the opposite of that observed since 1972, 81 eruptions (92%) and 7 intrusions (8%). Models with more realistic parameters show that the central cone should be much flatter (Annen et al., 2001).

This paper aims at understanding the origin of the atypical geometry of the central cone of Piton de la Fournaise. It examines the morphology and inner structure of the cone. It also considers the role of the magmatic and volcano-tectonic structures in both the growth and the deformation

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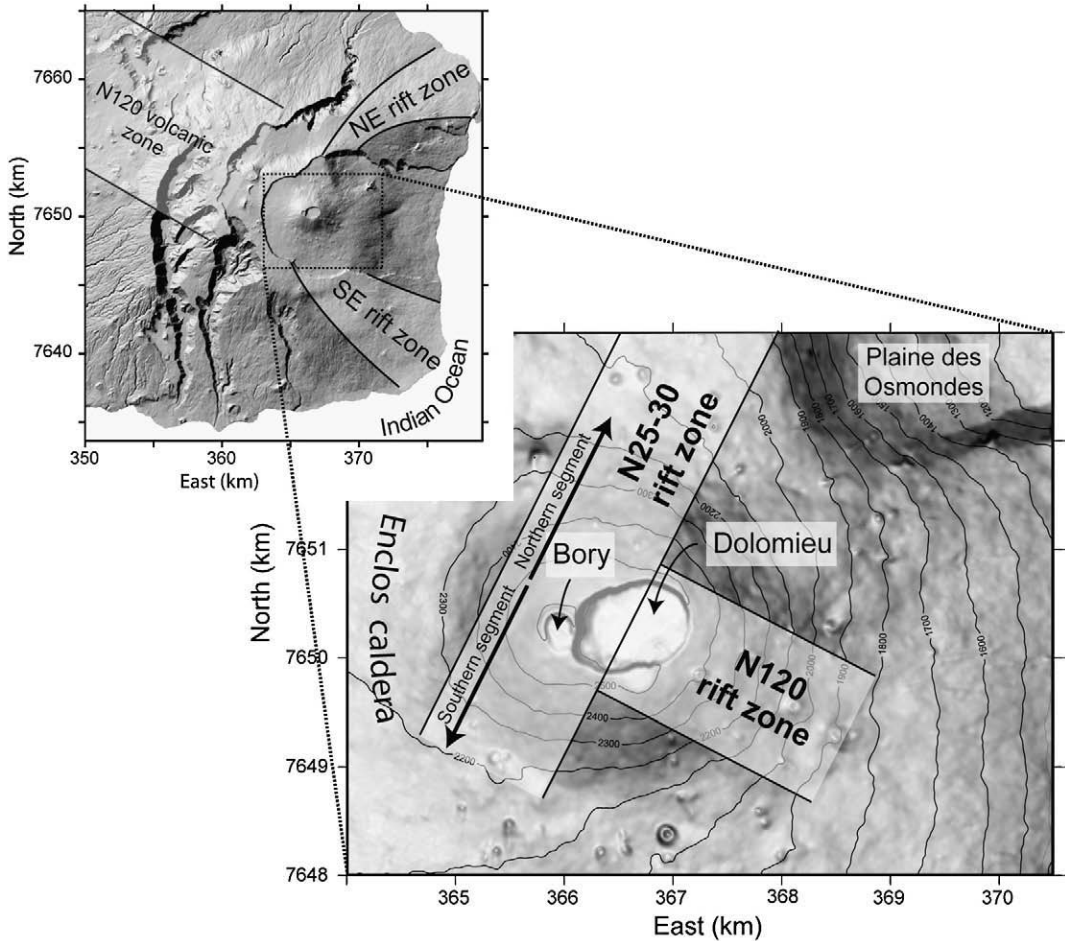

Fig. 1. 25-m step Digital Elevation Model of Piton de la Fournaise. The edifice is characterised by two NE and SE rift zones outside the Enclos caldera. In the Enclos caldera, the recent eruptions are concentrated along two N25–30 and N120 rift zones (Michon et al., 2007a). The central cone is cut by two summit collapse structures, Bory and Dolomieu. Coordinates in UTM WGS84 (zone 40S).

of the cone, by combining field data and GPS data, as well as numerical models of rift dyke intrusions. Such a multi-disciplinary approach highlights the existing links between the deformation observed in the field, the displacement measured by GPS, and the recurrent intrusions of the dykes along preferential paths. The origin of the central cone and its deformation are interpreted in the light of both endogenous and exogenous growths.

2. Morphology and inner structure of the central cone

Piton de la Fournaise is the active volcano of Réunion Island (Fig. 1). The eruptive centre is located in the upper part of a large U-shaped caldera, the Enclos-Grand Brûlé structure, where most of the eruptions have occurred in the past 4.5 ka (Bachèlery, 1981). The concentration of activity in the upper part of the caldera led to the construction of a 400-m-high cone. Magma intrusions, which originate from a magma chamber located at about sea level below the cone (Peltier et al., 2007), are concentrated along two N25–30 and N120 rift zones (Fig. 1; Michon et al., 2007a). Outside the Enclos caldera, magma intrusions may continue along the NE and SE rift zones. The present-day cone summit shows two collapse structures: Bory crater in the West, which is currently inactive, and Dolomieu in the East, which experienced a caldera collapse during the large April 2007 eruption (Fig. 1; Michon et al., 2007b). 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). As a whole, Bory and Dolomieu confer a global E–W elongation to the summit of the central cone.

The use of a 25-m step digital elevation model (DEM) provided by the Institut Géographique National allows a precise description of the limits of the cone, the distribution of the slopes and the structure of the summit zone. The cone's lower limit corresponds to an almost continuous sharp break-in-slope that separates the caldera floor and the steep flanks of the cone (Fig. 2). The local outlined discontinuities are due to the Puy Mi-Côte parasitic cone in the North, and the N120 topographic ridge in the SE, which is formed by the alignment of large pyroclastic cones along the N120 rift zone. These two structures disregarded, the base of the cone presents a sub-circular shape with a radius of about 1.6 km (Fig. 2a). The flanks of the cone present steep slopes, which contrast with the classical view of a basaltic effusive edifice. The western part of the cone, i.e., west of a N15-trending line centred on Dolomieu, is characterised by relatively homogeneous slopes ranging between 15° and 25°. East of the N15 boundary, the cone shows steeper slopes (25–30°), which locally reach 35°. Although the N120 topographic ridge gives to the southeast flank a complex slope distribution, the low-pass filtered DEM strikingly shows that the steep slopes of the cone's eastern half are not circumferentially distributed, but present two linear trends in the N150 and N55 directions (Fig. 2b). It is noteworthy that the N55 trend is aligned with a 500-m-wide and 700-m-long zone characterised by a network of parallel lineaments (Fig. 2c). Field observations and aerial photographs reveal that the lineaments correspond neither to the limit of lava flows, nor to eruptive