Tectonophysics 674 (2016) 195–209

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Evidence of sheared sills related to flank destabilization in a basaltic volcano

C. Berthod [a],*, V. Famin [a], J. Bascou [b], L. Michon [a], B. Ildefonse [c], P. Monié [c]

[a] *Laboratoire GéoSciences, Université de La Réunion, Institut de Physique du Globe de Paris, UMR 7154, Sorbonne Paris Cité, CNRS, 97744 Saint Denis, France*
[b] *Université de Lyon, Université Jean Monnet, UMR CNRS IRD 6524, Laboratoire Magmas et Volcans, F-42023 Saint Etienne, France*
[c] *Geosciences Montpellier, CNRS UMR 5243, Université de Montpellier 2, Place Bataillon, 34095 Montpellier, cedex 5, France*

ARTICLE INFO

Article history:
Received 22 October 2015
Received in revised form 2 February 2016
Accepted 8 February 2016
Available online 21 February 2016

Keywords:
La Réunion volcanoes
Sill
Magnetic fabric
Crystallographic fabric
Cointrusive displacement
Debris avalanche

ABSTRACT

Piton des Neiges basaltic volcano (La Réunion) has been deeply dissected by erosion, exposing large volumes of debris avalanche deposits. To shed light on the factors that led to volcano flank destabilizations, we studied the structure, the crystallographic and magnetic fabrics of the substratum of a debris avalanche unit. This substratum is a complex of >50 seaward-dipping sills that has been exposed by the avalanche. Structural observations show that the sill plane in contact with the avalanche is one of the latest intrusions in the sill complex. In this uppermost sill, the anisotropy of magnetic susceptibility (AMS) is correlated to the crystallographic preferred orientation of magmatic silicate minerals, allowing us to use AMS as a proxy to infer the magmatic flow. The AMS fabric across the intrusion is strongly asymmetric, which reveals that the contact sill was emplaced with a normal shear displacement of its hanging wall. The shear displacement and the magma flow in the intrusion are both directed toward the NNE, i.e. toward the sea, which is also the direction of the slope and of the debris avalanche runout. Because all the sills in the intrusion complex have a similar dip and dip direction, it is likely that several of them also underwent a cointrusive slip toward the NNE. We conclude that this cointrusive normal slip, repeated over many intrusions of the sill complex, increased the flank instability of the volcano. This incremental instability may have ended up into the observed debris avalanche deposit. At Piton de la Fournaise, the active volcano of La Réunion, sill intrusion and cointrusive flank displacement have been inferred from geophysical studies for the April 2007 eruption. By providing direct evidence of sheared sills, our study substantiates the idea that repeated sill intrusions may eventually trigger flank destabilizations in basaltic volcanoes.

1. Introduction

Destabilizations are rare but catastrophic processes of volcano flank failure, essentially known from their large-scale onshore and offshore deposits of debris avalanche breccia (Siebert, 1984; Moore et al., 1989; McGuire, 1996). The only observed example of such destabilization occurred during the eruption of Mount Saint Helens in May 1980 (Voight et al., 1981). Since then, coeruptive flank displacements have been documented at several volcanoes, like Kilauea in Hawaii (Montgomery-Brown et al., 2011), Mount Etna in Italy (Walter et al., 2005), and Piton de la Fournaise in La Réunion (Froger et al., 2015). Understanding how such displacements may evolve into destabilizations is important for volcanic risk management.

Coeruptive flank displacements may be driven by the combined effects of gravity and forceful magma injections (Swanson et al., 1976; Borgia, 1994; Lundgren, 2004). Forceful magma injection models assume that the volcano flank slides on a low-angle fault, pushed by the recurrent injection of magma into vertical rift zones (Dieterich, 1988). This model is problematic because it requires a combination of an elevated magma overpressure and an extreme pressurization of pore fluids to explain the lateral push of the edifice flank (Iverson, 1995; Elsworth and Day, 1999). It has also been proposed that pressure variations in the magma reservoir could result in a lateral displacement of volcano flanks (Walter et al., 2005). Another cause of coeruptive flank deformation could be the lateral creep of a viscous zone at the base of the volcano, such as high-temperature olivine cumulates (Clague and Delinguer, 1994), yielding an extensional stress field above shallow reservoirs in the edifice that would favor eruptions.

Based on observations of a debris avalanche deposit at Piton des Neiges (the extinct and eroded volcano of La Réunion Island), Famin and Michon (2010) proposed an alternative model in which coeruptive lateral displacement is caused by repeated intrusions of sills in a detachment fault zone. Each sill would activate slip on the detachment, progressively increasing flank instability and eventually leading to flank failure. This model has been tested by numerical simulations, which show that sill intrusions in a volcanic edifice under extension may indeed yield lateral flank displacements, and may also activate a

---

* Corresponding author.
E-mail address: carole.berthod@univ-reunion.fr (C. Berthod).

http://dx.doi.org/10.1016/j.tecto.2016.02.017

pre-existing detachment (Cayol et al., 2014; Chaput et al., 2014a). However, there is to date no observational constraints that sill intrusions cause a shear displacement during their emplacement.

The goal of this paper is to seek evidence of shear displacement during sill intrusions. To track such shear displacements, we studied the anisotropy of magnetic susceptibility (AMS) and the crystallographic fabrics of sill intrusions from the detachment and the "sill zone" (i.e. the stack of multiple sheeted sills) described by Famin and Michon (2010) and Chaput et al. (2014b). We combined this study with a structural reinvestigation of the sill zone in order to establish the chronology of deformation, intrusion, and destabilization events and to evaluate the structural impact of sills on the stability of a basaltic volcano, and thus their possible role in the initiation of flank failure.

2. Geological setting

La Réunion Island is composed of two volcanoes, Piton des Neiges, inactive and deeply incised by erosion, and Piton de la Fournaise, currently active and built on the southeastern flank of Piton des Neiges (Fig. 1). Our study focuses on Piton des Neiges, which occupies the northwestern two third of the island and culminates at an altitude of 3070 m above sea level. Piton des Neiges represents the most ancient preserved subaerial activity of La Réunion Island, as its oldest lavas have yielded K–Ar ages up to 2.17 ± 0.03 Ma on the northern slop of the edifice Quidelleur et al. (2010), Fig. 1. From at least 2.17 Ma to 430 ka, Piton des Neiges underwent a stage of shield building, with an effusive eruptive style and the emission of mafic magmas. Then, after a 90 ka period of quiescence and erosion, the volcano entered into a post-shield stage at about 340 ka, with a more explosive activity and a production dominated by alkaline and differentiated magmas (Kluska, 1997). The end of Piton des Neiges activity has been dated at 29 ± 3.0 ka by the K–Ar method (Gillot and Nativel, 1982) or 12.5 ± 3.0 ka by the U–Th method Deniel et al. (1992). In the course of its magmatic activity, Piton des Neiges has been affected by several destabilizations, as demonstrated by the presence of large volumes of debris avalanche breccias (Fig. 1). It is, however, unclear whether these large deposits are related to a small number of large and catastrophic avalanches or to multiple small destabilizations (Bachèlery et al., 2003; Bret et al., 2003; Oehler et al., 2004, 2007; Famin and Michon, 2010; Salvany et al., 2012).

The morphology of Piton des Neiges is characterized by three major depressions, the cirques of Cilaos, Mafate and Salazie. These depressions have been successively interpreted as scars of massive destabilizations (Bret et al., 2003; Oehler et al., 2004; Oehler et al., 2007), as the result of the subsidence of intrusive complexes after the end of volcanic activity (Gailler and Lénat, 2010), or as erosional structures (Salvany et al., 2012). Whatever the mechanism involved in their formation, the cirques have been preferentially incised by erosion, which enables the observation of the internal structure of the volcano. Taking advantage of this morphology, Famin and Michon (2010) reported the presence of a major detachment (i.e. a low-angle, outward-dipping normal fault) in the cirque of Salazie. The footwall of this detachment is a yet undated gabbroic intrusion interpreted as an extinct magmatic chamber of Piton des Neiges (Chevallier and Vatin-Perignon, 1982). The hanging wall of the detachment is an also undated breccia interpreted as a debris avalanche deposit (Famin and Michon, 2010). The mafic composition of breccia suggests that the debris avalanche is older than the post-shield stage of Piton des Neiges (i.e., older than 340 ka). The detachment itself is characterized by an intense ductile and brittle shear deformation toward the NE, localized within a ~10-m-thick zone in the footwall. Sheared rocks are also heavily affected by hydrothermal alteration to greenschist facies. The gabbroic footwall is separated from the breccia hanging wall by a 50-m-thick sill zone injected in the lithological discontinuity of the detachment (Chaput et al., 2014b). Sills are composed of olivine-rich basalt, which suggests that they occurred during the shield building stage of Piton des Neiges. Lenses of sheared and altered gabbro are pinched between the sills. Some sills in the sill zone are themselves heavily sheared, faulted, and altered, implying that

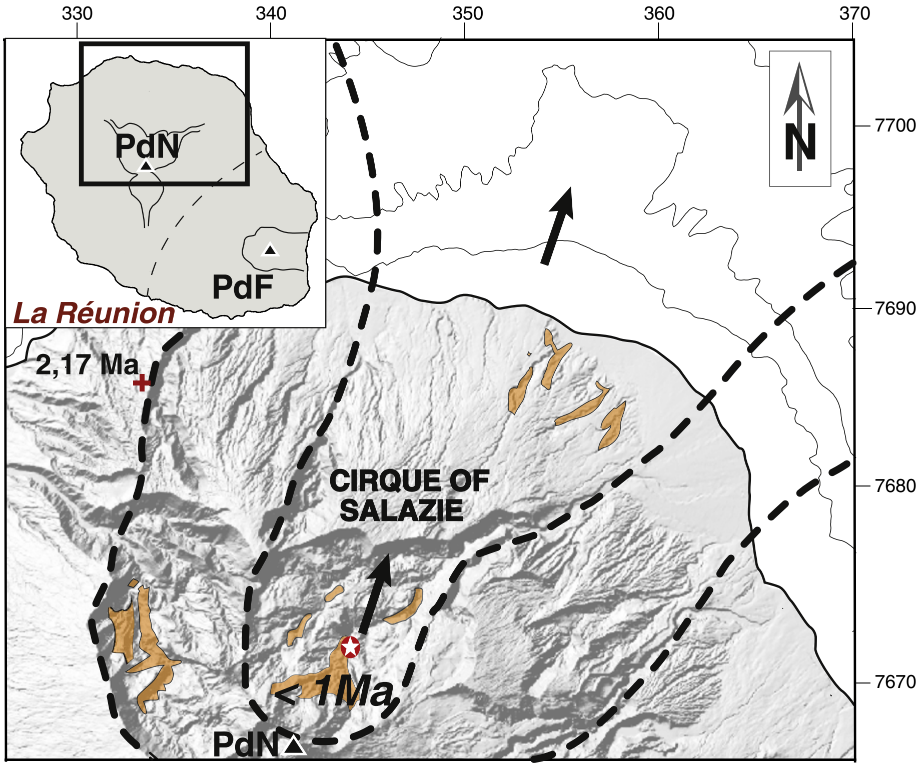

Fig. 1. Digital elevation model of the northern part of La Réunion Island. The black arrows represent the direction of destabilization proposed by Oehler et al. (2004, 2007) and observed by Famin and Michon (2010) on the studied outcrop (white star). The proposed destabilization scars (dashed lines) and the delineation of debris avalanche breccias (brown zones) is from Bret et al. (2003) and Oehler et al. (2004, 2008). PdN stands for Piton des Neiges, PdF for Piton de la Fournaise. Coordinates in kilometers (UTM, WGS84).