A new model for the evolution of La Réunion volcanic complex from complete marine geophysical surveys

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[1] Results from recent marine geophysical surveys offer a new perspective for characterizing the evolution processes of volcanic islands. In 2006, cruises FOREVER and ERODER 1 investigated the submarine flanks and the surrounding abyssal plain of La Réunion (Indian Ocean) to obtain for the first time a complete geophysical survey of the area. Combined analyses of these data reveal major differences in the evolution of the two emerged volcanoes, Piton des Neiges and Piton de la Fournaise. We show that debris avalanche deposits extend on the abyssal plain only offshore the active Piton de la Fournaise volcano attesting the occurrence of large flank-collapse events. The absence of such deposits offshore Piton des Neiges and the presence of compressive structures within the sedimentary unit below the edifice support a mechanism of slow deformation of this volcano, such as sliding or spreading. The slow deformation of Piton des Neiges has led to numerous secondary submarine slope instabilities and favored some unconfined turbidity flows which generated large sediment waves running downward all around the island. This study proposes a new model using the most complete marine data set available: slow deformation controls the evolution of Piton des Neiges whereas Piton de la Fournaise (formed on the flanks of a pre-existing edifice) experienced catastrophic, large flank-collapse events. **Citation:** Le Friant, A., E. Lebas, V. Clément, G. Boudon, C. Deplus, B. de Voogd, and P. Bachèlery (2011), A new model for the evolution of La Réunion volcanic complex from complete marine geophysical surveys, *Geophys. Res. Lett.*, *38*, L09312, doi:10.1029/2011GL047489.

1. Introduction

[2] Flank-collapses and volcanic spreading play a significant role in the evolution of volcanic edifices. Both are increasingly recognized as efficient processes of volcano destruction whatever the geodynamic context [e.g., *Moore et al.*, 1989; *Holcomb and Searle*, 1991; *McGuire*, 1996; *Morgan et al.*, 2003; *Romagnoli et al.*, 2009]. When they occur on volcanic islands, material can enter the sea and produce catastrophic tsunamis. La Réunion is a 7000 m-high voluminous volcanic complex with a large submarine part and two emerged volcanoes (Piton des Neiges and Piton de la Fournaise). Previous interpretations have considered large sector collapse to be the main process occurring on La Réunion volcanoes [*Lénat et al.*, 1990; *Labazuy*, 1996; *Ollier et al.*, 1998; *Bachèlery et al.*, 2003; *Oehler et al.*, 2008] although volcano gravitational spreading has also been proposed for the subaerial part [*Oehler et al.*, 2005; *Delcamp et al.*, 2008; *Michon and Saint-Ange*, 2008]. However those results suffer from uncertainties linked to the limited coverage of geophysical surveys on La Réunion submarine flanks. Previous data were mostly swath bathymetry collected during transits around the island and did not allow a complete view of the seafloor. Criteria for the identification of offshore debris avalanche deposits from marine data have been developed by several authors in different contexts [e.g., *Moore et al.*, 1989; *Deplus et al.*, 2001; *Le Friant et al.*, 2003]. They all show that combined analysis of swath bathymetry, backscatter data, 3.5 kHz echo sounder and seismic reflection profiles is essential to characterize the nature of the submarine flanks. New marine data have been collected in 2006 and provide for the first time a complete high-resolution geophysical survey of La Réunion submarine flanks and the surrounding oceanic plate. The data set allows to study the flanks of the volcanic edifice as a whole to address questions such as: How mass-wasting processes occurred around La Réunion? What is the relative importance of submarine slope instabilities versus large subaerial volcano flank-collapses? Do the two main volcanoes of La Réunion (Piton des Neiges and Piton de la Fournaise) have the same evolution?

[3] This contribution provides an analysis of La Réunion volcanoes from an offshore perspective by using the most complete marine geophysical dataset available. First, analysis of the 3.5 kHz echo sounder profiles combined to swath bathymetry, reflectivity and slope maps constrains the morphological and textural characteristics of the submarine flanks while seismic reflection profiles analysis allows a depth investigation. Second, we discuss the main processes that occurred offshore Piton des Neiges and Piton de la Fournaise volcanoes in term of mass-wasting processes. We then propose new constraints for the evolution of La Réunion volcanoes and open new perspectives to understand the evolution of the volcanic complex.

2. Geological Context

[4] La Réunion (Indian Ocean) is a volcanic island resulting from the activity of a hot spot [*Duncan et al.*, 1989]. Piton des Neiges and Piton de la Fournaise are the two emerged

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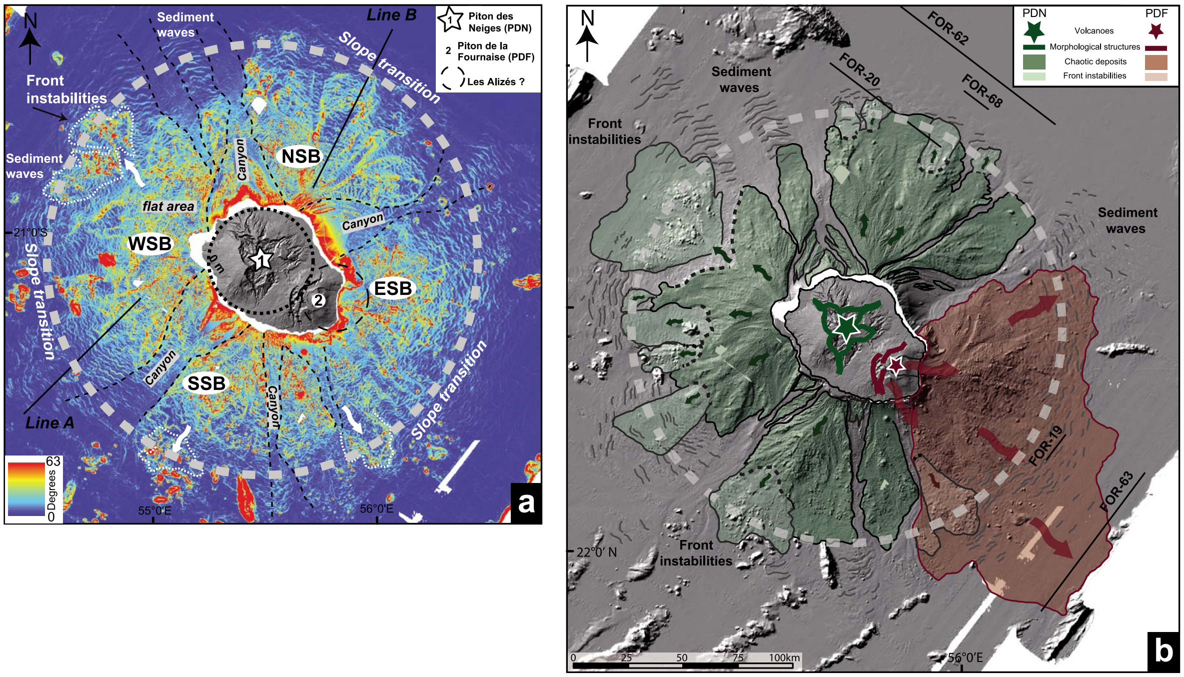

Figure 1. (a) Slopes of the sea bottom topography computed from FOREVER and ERODER1 swath bathymetry around La Réunion island (on land topography data provided by IGN France). NSB, WSB, SSB, ESB are the four morphological bulges from *Labazuy* [1996]. The numbers 1 and 2 indicate the location of the two main volcanoes: Piton des Neiges and Piton de la Fournaise, respectively. Les Alizés volcano could be located beneath the Piton de la Fournaise volcano. Such a representation enhances the main morphological structures of La Réunion submarine flanks: canyons, main slope transition, sediment waves and front instabilities. The base of the whole volcanic complex (at the slope transition) can be approximated by the dashed thick circle centred on the summit area of Piton des Neiges (radius: ~100 km). (b) Combined bathymetry and topography data of La Réunion island and submarine flanks illuminated from N315°, with interpretation of mass-wasting processes. The extent of rough and chaotic terrains is mapped. The small green arrows indicate the direction of the submarine failures on Piton des Neiges submarine flanks. Secondary front instabilities are mapped in light green. The dashed thick circle centred on the central summit area of the Piton des Neiges volcano is the same as on Figure 1a. The red arrows indicate the eastern direction of the large volcano flank-collapse events occurring on Piton de la Fournaise.

volcanoes and culminate respectively at 3000 m and 2600 m above sea level (Figure 1). The existence of a third volcano, 'Les Alizés' [*Lénat et al.*, 2001], located beneath the present Piton de la Fournaise volcano, has been suggested as a proto Fournaise, being now completely dismantled. Piton des Neiges emerged before 2.1 Ma [*McDougall*, 1971] and its last activity occurred at around 12 ka [*Deniel et al.*, 1992]. This dormant volcano is now deeply eroded and dissected in its central part by three large depressions or 'cirques' which feed several sedimentary submarine fans [*Saint-Ange et al.*, 2011]. Piton de la Fournaise has been growing for at least the last 0.527 Ma [*Gillot and Nativel*, 1989]. The main constructional phase of this active volcano was contemporaneous with the end of Piton des Neiges activity.

3. Data and Methods

[5] In 2006 we conducted two marine geophysical surveys off La Réunion: FOREVER and ERODER 1, on the French oceanographic vessels N/O L'Atalante and BHO Beautemps-Beaupré, respectively. We obtained, for the first time, a full coverage of La Réunion submarine flanks and of the surrounding oceanic plate with high-resolution data. Most of the data have been collected during cruise FOREVER: Simrad EM12D swath bathymetry and backscatter data, 3.5 kHz echo sounder and 24-channel seismic reflection profiles. During cruise ERODER 1 we completed the survey on the upper slopes of the volcanic edifice with Simrad EM120 swath bathymetry and backscatter data. Navigation was achieved using GPS, thus allowing a ship position accuracy of a few meters. We constructed digital elevation models (DEM) with resolutions from 50 to 250 m, depending on the depth of the surrounding seafloor. The 24-channel seismic reflection lines were stacked, filtered and migrated using seawater velocity.

4. Analysis of the Seafloor Data

4.1. Morphology

[6] Sea bottom morphology analysis allows investigation of the submarine slope transition which approximates the base of La Réunion volcanic complex on the oceanic floor. The transition between the volcanic complex and the surrounding seafloor is clearly defined on the slopes map of the sea bottom topography (Figure 1a). We observe before the slope transition a distinct morphological front/bench (Figures 1, 2a, and 2b). This front collapsed in many places generating local submarine scarps associated to front instabilities deposits (Figure 1). The slope transition between the volcanic complex and the surrounding seafloor is located at ~60 km from the coastline to the south−east (east of Piton de la Fournaise volcano), whereas in other directions it is located at

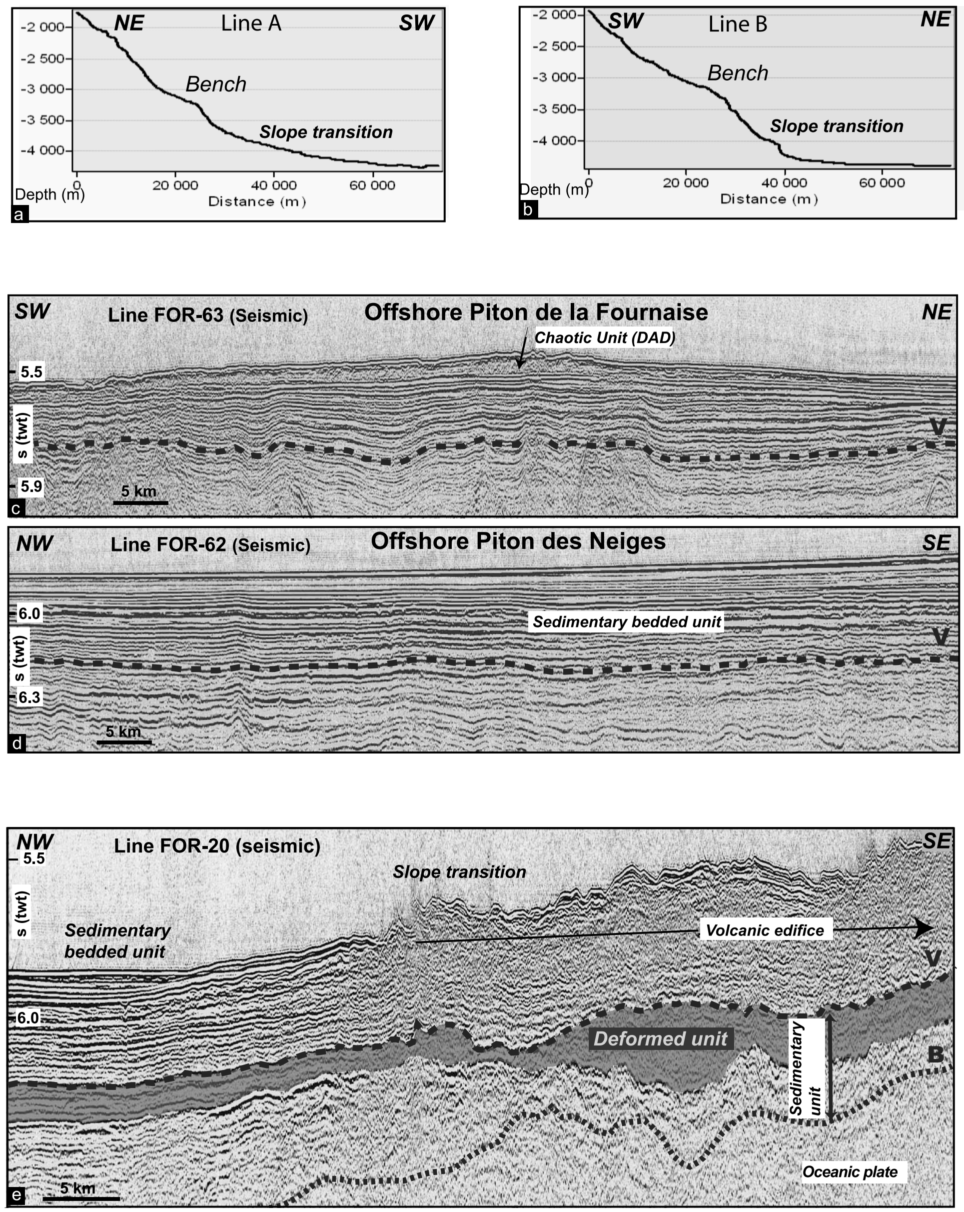

Figure 2. The locations of profiles (bathymetry, 3.5 kHz echo sounder and seismic reflection) are shown on Figure 1. (a and b) Lines A and B cross the submarine flanks of Piton des Neiges volcano and illustrate the presence of a bench before the slope transition, respectively. (c and d) Two contrasting profiles in the abyssal plain offshore Piton de la Fournaise and Piton des Neiges volcanoes, respectively. Offshore Piton de la Fournaise a debris avalanche deposit unit is clearly identified which contrasts with the regular sedimentation offshore Piton des Neiges. (e) Line FOR-20 crosses the submarine flanks of Piton des Neiges and shows the slope transition between the volcanic edifice and the surrounding seafloor. V: base of the volcanic edifice tied to the interpretation of *de Voogd et al.* [1999]; B: top of oceanic basement. Between B and V the sedimentary unit is deformed beneath the volcano.

~75 km. However, it is always located at the same distance (~100 km) from the central area of Piton des Neiges. In addition, the submarine base of La Réunion island has a circular shape (radius: ~100 km) whereas the subaerial part is elongated (Figure 1).

[7] Four main canyons deeply erode and divide the submarine flanks into 'four large fan-shaped bulges' which have been previously named [*Labazuy*, 1996]: the northern (NSB), eastern (ESB), southern (SSB) and western (WSB) submarine bulges (Figure 1a).

4.2. Acoustic and Seismic Character

[8] Joint analysis of our new, complete, high-resolution dataset (3.5 kHz echo sounder facies, bathymetry and seismic reflection) allows for the textural characterization of La Réunion submarine flanks. Rough and chaotic terrains constitute the submarine flanks and attest to the presence of

debris avalanche deposits using usual criteria (e.g., Hawaii [*Moore et al.*, 1989]; La Palma [*Urgeles et al.*, 1999], and Lesser Antilles [*Deplus et al.*, 2001; *Boudon et al.*, 2007]). On the reflectivity map, a speckled pattern typical of debris avalanche deposits [e.g., *Moore et al.*, 1989] is mainly recognized offshore Piton de la Fournaise (Figure S1 of the auxiliary material). On 3.5 kHz echo sounder and seismic reflection profiles, the chaotic deposits display hyperbolic facies and chaotic/transparent reflectors respectively, contrasting with sedimentary units (Figure S2). Offshore Piton des Neiges, the chaotic terrains are covered by a well-bedded sedimentary unit on 3.5 kHz profiles. The analysis of combined data allows for delimitation of the rough and chaotic terrains extent. Figure 1b highlights two distinct behaviors of Piton de la Fournaise and Piton des Neiges submarine flanks. Offshore Piton de la Fournaise rough and chaotic terrains clearly extend on the abyssal plain (Figures 1b and 2c). Offshore Piton des Neiges, no distinct chaotic unit is observed on seismic reflection profiles after the slope transition, which indicates that rough and chaotic terrains end at the slope transition (Figure 2d). This observation highlights the absence of large submarine debris avalanche deposits on the abyssal plain off Piton des Neiges volcano, conversely to Piton de la Fournaise.

5. Discussion

5.1. Comparison of Piton des Neiges and Piton de la Fournaise

[9] The base of La Réunion volcanic complex is always located at the same distance (~100 km) from the central area of Piton des Neiges, circle on Figure 1. This observation suggests that Piton des Neiges probably controls the whole geometry of La Réunion. It seems to be a large volcano in comparison with Piton de la Fournaise and Les Alizés volcanoes.

[10] The absence of large debris avalanche deposits on the abyssal plain offshore Piton des Neiges and the extent of the chaotic deposits that always end at the same distance on the submarine flanks, contrast with most volcanic islands (e.g., Hawaii [*Moore et al.*, 1989], Canary [*Urgeles et al.*, 1999] or Lesser Antilles [*Deplus et al.*, 2001; *Le Friant et al.*, 2003; *Boudon et al.*, 2007]), where large subaerial sector collapses occurred. Such flank collapses produced large debris avalanche deposits which extend further than the base of the volcano on the abyssal plain. They have various runout lengths depending on the volume of material involved, and occurred toward particular directions due to preferential areas of weakness (structural, hydrothermal or regional origin). In addition, high-resolution seismic reflection profiles show that sediments cover the flanks of the Piton des Neiges volcano (in average ~30 m, sometimes more on Figure 2e). Using a sedimentation rate of 2 cm/ka [*Fretzdorff et al.*, 2000], our data suggest that no large slides occurred on the volcano since at least 1Ma. From an offshore perspective, large on-land sector collapses producing debris avalanches flowing offshore Piton des Neiges is therefore unlikely to explain the evolution of the edifice, although small but frequent instabilities could occur.

[11] For Piton de la Fournaise, debris avalanche deposits recognized offshore can be related to large on-shore horseshoe-shaped structures (Figure 1b) as previously proposed [*Lénat et al.*, 1990; *Labazuy*, 1996; *Oehler et al.*, 2008]. Here, we give evidence for larger debris avalanche deposits extending farther from the volcano. They could be related to older instabilities that affected Piton de la Fournaise as attested by the thin sedimentary layers covering the chaotic deposits (Figure 2c in places, 3.5 kHz echo sounder profiles).

5.2. Long-Term Evolution of Piton des Neiges Volcano

[12] The offshore analysis of Piton des Neiges highlights important features that constrain the evolution of the volcano. First, the bench and the slope transition all around the island are consistently located at the same distance from the central area of Piton des Neiges. Second, the submarine flanks are dismantled and the characteristics of the chaotic deposits, which do not extend on the abyssal plain, are closer to slow cohesive slump behavior rather than debris avalanche one [*Moore et al.*, 1989]. Third, seismic reflection profiles clearly show the transition between the edifice and the surrounding bedded sedimentary unit, and the construction of the voluminous La Réunion volcanic complex on a sequence of sediments over the oceanic plate (Figure 2e). Previous seismic data have identified two seismic horizons labelled B and V (cruise REUSIS [*de Voogd et al.*, 1999], Figure S3). B is the top of the oceanic basement that can be recognized on most of the FOREVER seismic profiles [*Deplus et al.*, 2007]. V marks the base of the volcanic complex and contemporaneous deposits in the surrounding abyssal plain. Thus, the seismic unit between B and V is interpreted as the oceanic sediments that predate the construction of the volcanic edifice. Significant thickness variations of this unit are mainly due to basement topography, but below the edifice, one sedimentary unit is strongly deformed (Figure 2e). These compressive structures attest to the deformation of the sedimentary unit below the edifice as described for spreading of volcanoes [*Borgia*, 1994; *Borgia et al.*, 2000; *van Wyk de Vries and Borgia*, 1996; *van Wyk de Vries and Francis* 1997; *Wooller et al.*, 2004]. In addition, *de Voogd et al.* [1999] suggested that sediments may act as a decollement surface with associated compressional structures (Figure S3). All these observations are in favour of slow deformation such as sliding or spreading controlling the evolution of Piton des Neiges volcano. We propose that the slow deformation of the volcano leads to numerous secondary submarine slope instabilities that explain the chaotic texture of the submarine flanks. In addition, based on on-land studies and scaled laboratory experiments *Merle and Borgia* [1996], *Oehler et al.* [2005] and *Delcamp et al.* [2008] have interpreted the three major depressions in the summit part of Piton des Neiges (Figure 1) as potential radial intersecting grabens due to the spreading of the volcano. Lastly, our offshore analysis is consistent with slow deformation observed on land within the cirques of Piton des Neiges volcano [*Famin and Michon*, 2010].

5.3. Sediment Waves

[13] The sedimentary unit around the island displays large undulations with wavelengths of several km, radially distributed, which extend up to 30 km from the slope transition (Figure 1). These concentric sediment waves are morphologically similar to those found at the base of Tharsis Rise on Mars. In oceanic context, such trains of waves are commonly observed as offshore La Palma island (Canary) [*Wynn et al.*, 2000] where they have been interpreted as

being formed by unconfined turbidity currents originating on the volcano flanks. Around La Réunion the unconfined turbidity flows could be related to the spreading of the volcano which continuously dismantled the superficial part of the volcano flanks. In addition, chaotic terrains serve as irregularities to form sediment waves. When located on the sides of sedimentary fan paths, the large wavelength sediment waves can also be related to active channel sedimentary processes [*Wynn et al.*, 2000; *Saint-Ange et al.*, 2011].

5.4. Summary

[14] Volcanoes from La Réunion display two distinct behaviors during their evolution. Slow deformation such as spreading is probably one of the main processes controlling the overall morphology of the submarine flanks of Piton des Neiges. The absence of lithospheric flexure beneath La Réunion [*de Voogd et al.*, 1999] may influence the development of spreading. As a consequence of slow deformation, the flanks of Piton des Neiges have been continuously dismantled by superficial landslides both on land [*Bachèlery et al.*, 2003] and on the submarine parts (Figure 1). In some cases, larger instabilities have been produced near the coast or at the submarine bench. The dismantling of the flanks triggered some unconfined turbidity flows which generated large sediment waves [*Wynn et al.*, 2000] running downward all around the island. Piton de la Fournaise volcano formed on the south−eastern flank of a proto-volcano (Piton des Neiges or Les Alizés). Such a location has led Piton de la Fournaise to collapse several times in the same direction, toward the sea, generating characteristic imbricated large open structures on land and several voluminous debris avalanches that flowed down the submarine flanks onto the oceanic plate (Figure 1b). The difference in behavior between the two volcanoes is probably due to the fact that Piton des Neiges was first an isolated circular submarine volcano built on sediments that favour radial spreading, while Piton de la Fournaise was emplaced on the flank of a pre-existing edifice. We consider that Piton des Neiges constitutes a reference natural system which could be used and compared with volcanoes in other settings [e.g., *Morgan et al.*, 2003]. It is likely that the slow deformation described here exerts an influence on magma ascent and storage, eruptive dynamics and geomorphological evolution with implications for risk evaluations.

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