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RESEARCH ARTICLE

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Recurrence of major flank landslides during the last 2-Ma-history of Reunion Island

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Abstract New detailed swath bathymetry and backscatter data corroborate the existence of four large bulges on the submarine flanks of Reunion Island. These fan-shaped promontories are 20–25 km wide at the coastline and 70–150 km across the seafloor 40–50 km offshore. Their surfaces are characterized by a speckle sonar pattern, indicating the presence of large blocks up to several hundred meters across. Each bulge results from the superposition of multiple landslide deposits whose older ones are dissected and delimited by erosive channels as much as 200 m deep and 20 km long. The submarine flanks of Reunion Island are thus mostly built by accumulation of debris avalanche fans. Morphologic and geologic evidence define large subaerial source areas for these mass-wasting events. In particular, inferred headwalls of most landslides having affected the Piton des Neiges massif generally coincide with the boundaries of its "cirques" (Mafate, Salazie, and Cilaos), whereas recurrent landslides have resulted in the formation of large concentric amphitheatre structures through the Piton de la Fournaise massif. Thus, about 15 slide events accompanied growth of the Reunion Island shield since 2 Ma.

Keywords Reunion Island · Piton des Neiges · Piton de la Fournaise · EM12D multi-beam data · Flank landslides · Debris avalanches · Oceanic island evolution

Introduction

The development of mechanical instabilities in volcanic edifices results in flank landslides. Landslide deposits have been frequently identified on volcanoes in both emerged and submerged environments. The best-documented example of a subaerial flank landslide is that of Mount St Helens on 18 May 1980, which triggered a paroxysmal eruption (Lipman and Mullineaux 1981). The development of sophisticated bathymetric and sonar imagery techniques have been crucial in recognizing slide material on the submarine flanks of many volcanic islands in the last two decades. The Hawaiian Ridge was affected by at least 68 large mass-wasting events, with associated deposits attaining 200 km in length and about 5,000 km^3 in volume (Moore et al. 1989, 1994). The Canary Islands similarly experienced 18 mass-wasting events involving up to 1,000 km^3 of material (Ablay and Hürlimann 2000; Krastel et al. 2001). Similar deposits were also identified around the Marquesas Islands (Filmer et al. 1994), Tahiti Island (Clouard et al. 2001), and Tristan da Cunha Island (Holcomb and Searle 1991). These examples emphasize the importance of these phenomena for oceanic islands. More recently, an extensive survey of the submerged flanks of volcanic islands of the Lesser Antilles revealed the presence of at least 30 flank landslides (Deplus et al. 2001; Le Friant 2001). Therefore, mass-wasting phenomena seem to represent a common and recurrent process during the growth and evolution of volcanoes in various geodynamical settings. Flank landslides affect steep strato volcanoes at active margins, as well as intraplate oceanic shields with more gentle slopes, previously considered as more stable edifices.

The Reunion Island oceanic shield has been studied extensively since the 1980s. In particular, recent geophysical studies have provided valuable data on the interior of the island through seismic (Charvis et al. 1999; de Voogd et al. 1999; Gallart et al. 1999), gravity (Malengreau et al. 1999), and magnetic investigations (Lénat et al. 2001). However, the geological structure and the evolution of this volcanic system remain insufficiently understood, partly due to a lack of studies on its submarine part. Indeed, the emergent part of the island represents only 3% of the total volume of the edifice (de Voogd et al. 1999), and a major part of the story is to be found on the submerged flanks. Only the eastern flank of the island has been studied in

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detail (Lénat and Labazuy 1990; Lénat et al. 1989, 1990; Labazuy 1991, 1996; Bachèlery et al. 1996; Ollier et al. 1998; de Voogd et al. 1999). This work has revealed that this area of the island was affected by at least three major landslides involving up to 500 km^3 of subaerial material. Previously available general bathymetry at the scale of the island suggested that deposits of similar or more considerable volume could exist in other submarine areas of Reunion Island (Lénat and Labazuy 1990; Labazuy 1991, 1996). However, the absence of detailed bathymetric data beyond the eastern flank of the island has precluded any detailed analysis.

The work presented here is based on new multibeam bathymetric and acoustic data, acquired along transit routes to and from Reunion Island during three cruises of the IFREMER R/V L'Atalante in 1995. The data partially cover the southern, eastern, and northern submarine flanks of the island. The analysis of this new data set enables us to confirm and validate the presence of landslide deposits in several areas off Reunion Island. The subaerial source regions for the mass-wasting events are proposed. The results are compared with the present geological knowledge on Reunion Island and synthesized into a new scheme of evolution of this oceanic island for the last 2 Ma.

Geological setting and previous work

Reunion Island is an oceanic shield volcano located in the southernmost part of the Mascarene Basin (southeastern Indian Ocean) 750 km east of Madagascar (Fig. 1). It is a 8–9-km-high elliptical flattened volcanic cone 220–240 km in diameter at the level of the surrounding sea floor. Its growth is attributed to the activity of a mantle hot spot whose origin is still controversial (Duncan et al. 1989; Burke 1996). The beginning of volcanism on Reunion Island is unknown but can be reasonably estimated at more than 5 Ma (Gillot et al. 1994). The first evidence of its subaerial activity dates from about 2 Ma (McDougall 1971).

For a long time, Reunion Island has been interpreted as resulting from the juxtaposition of two volcanoes: Piton des Neiges and Piton de la Fournaise (Chevallier and Vatin-Pérignon 1982). The construction of the subaerial part of Piton des Neiges corresponds to the formation of a basaltic shield between 2.08 Ma and 430 ka (Oceanite Series); then, after a hiatus and period of erosion, to the eruption of differentiated alkaline magmas between 330 and 12 ka (Differentiated Series; McDougall 1971; Gillot and Nativel 1982; Deniel et al. 1992). Its present morphology is complex and characterized by three major depressions: the cirques of Cilaos, Mafate and Salazie. The origin of these depressions is not fully understood, but they are interpreted as the result of vigorous tropical erosion and volcano-tectonic events. Piton de la Fournaise, presently one of the world's most active volcanoes, is a basaltic shield whose oldest outcropping lava flows have been dated to 0.527 Ma (Gillot and Nativel 1989). Its present effusive eruptions essentially take place on its central cone and along its northeast and southeast rift zones.

Recent geophysical studies (Charvis et al. 1999; de Voogd et al. 1999; Gallart et al. 1999; Malengreau et al. 1999; Lénat et al. 2001) are in disagreement with this two-volcano model. The evolution model proposed by Lénat et al. (2001) is more complex. It comprises (1) the activity of two major primitive volcanic systems, Piton des Neiges in the northwest part of the island and Les Alizés volcano in the southeast; (2) the possible contribution of a third focus, Takamaka volcano, in the northeast of the axis, which connects the major centers; (3) the

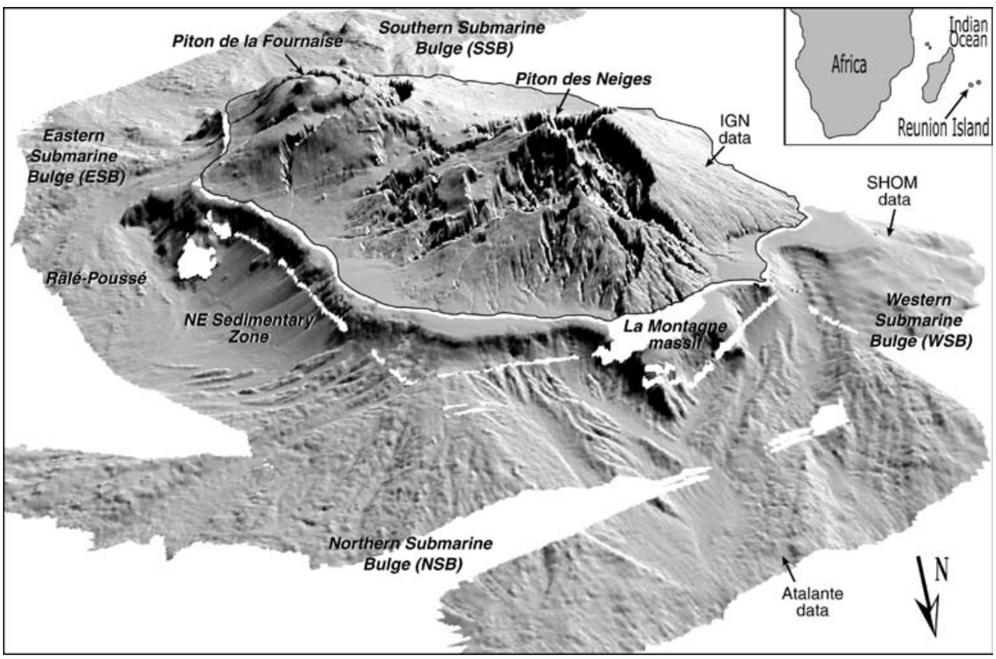


Fig. 1 Three-dimensional representation of the emerged and submerged flanks of the Reunion Island edifice (×4 vertical exaggeration). Global 100-m-gridded DTM with *shaded-relief overlay* (apparent illumination from the southwest). Inset shows the location of Reunion Island in the Indian Ocean

building of a fourth, younger system, Piton de la Fournaise, on the flanks of three pre-existing volcanoes; and (4) repeated destructive episodes of these volcanic massifs during their growth. The associated flank landslides are postulated to have taken place on nearly all the flanks of the island. This hypothesis is supported by the morphology of submarine slopes, which shows four large bathymetric bulges to the north, west, south, and east of Reunion Island (Lénat and Labazuy 1990; Labazuy 1991, 1996). These structures were first interpreted as sedimen-tary aprons resulting from large-scale erosional dismantling of the island (Kieffer 1990). However, detailed studies confirm the mass-wasting origin of the eastern bulge and suggest a similar origin for the other submarine bulges. The results from magnetic and seismic work are in agreement with this interpretation. The absence of magnetic anomalies on submarine flanks of the island suggests that they are mostly constituted by disorganized material (Lénat et al. 2001). Seismic reflection profiles off Reunion Island (de Voogd et al. 1999) reveal the presence of debris avalanches deposits in the southern submarine parts of Piton des Neiges and Piton de la Fournaise massifs.

Data acquisition and processing

The work presented here is based on new Simrad EM12D swath bathymetry and backscatter data collected in 1995 during IFREMER R/V L'Atalante cruises to and from Reunion Island harbor (Gallieni, Larjaka, and Djire cruises). These data partly cover the east and south submerged flanks of Piton de la Fournaise, as well as the north and east areas of Piton des Neiges (Fig. 1). Preliminary processing was performed by IFREMER in order to generate (1) a 100-m gridded digital terrain model (DTM) of the bathymetry and (2) three associated 25-m gridded acoustic images of the north, northeast, and east–southeast submarine zones that cover the same area as the bathymetry. The resulting georeferenced data were supplied in Mercator projection, using the WGS84 ellipsoid as reference.

To obtain a view of the whole edifice, we have mosaicked the acoustic images and constructed a DTM, integrating both submarine and subaerial areas (Fig. 1). As most of the bathymetry was based on Atalante data, we chose to represent this final global DTM in geographical coordinates using the WGS84 ellipsoid as a reference. The bathymetry near the seashore was completed using data digitized from maps derived from conventional detailed bathymetry by the "Service Hydrographique et Océanographique de la Marine" (SHOM). The subaerial topography came from a 100-m gridded DTM of the French "Institut Géographique National" (IGN). These complementary data were available in a local projection system (Gauss-Laborde or Reunion Island Piton des Neiges projection) using the 1924 International ellipsoid. The conversion to the WGS84 ellipsoid and the Mercator projection was performed with software provided by the IGN. The data sets were merged in a 100-m-gridded global DTM. Atalante acoustic images were assembled in a 25-m-gridded sonar mosaic.

Description and analysis of the submerged part of Reunion Island

The new bathymetric and acoustic data confirm the existence of at least four large submarine bulges to the north, west, south, and east of the island (Fig. 1). Our work focuses on the first three bathymetric structures, as the Eastern Submarine Bulge (ESB) already has been interpreted in detail (Lénat and Labazuy 1990; Lénat et al. 1989, 1990; Labazuy 1991, 1996; Bachèlery et al. 1996; Ollier et al. 1998; de Voogd et al. 1999). The Northern Submarine Bulge (NSB) has the best data coverage and was therefore analyzed in greater detail, whereas data coverage allows the study of only the north part of the Western Submarine Bulge (WSB) and of the east part of the Southern Submarine Bulge (SSB).

The Northern Submarine Bulge (NSB)

The NSB covers the entire northeast quarter off the island (Fig. 2). It forms a fan-shaped submarine promontory, about 20 km wide at the seashore to nearly 70 km on the surrounding sea floor. It extends about 40 km offshore.

The surface of the NSB is characterized by generally low sonar backscatter values (Fig. 2b), which principally correspond to rough surfaces on the bathymetry (Fig. 2a). In addition, spots of high sonar backscatter are observed on some zones of the low-sonar backscatter areas (not all are visible at the scale of the figures). This speckled pattern indicates the presence of blocks protruding from the surface. The largest, which are up to several hundred meters wide, also can be recognized on the bathymetry. The generally low-sonar backscatter of the NSB indicates a near specular reflection of the sonar waves and therefore a smooth surface, probably a coating of fine-grained sediments. The high-backscatter spots are attributed to reflection on block facets oriented nearly perpendicular to the incident sonar waves.

The NSB is notched by high-backscatter channels that exhibit a relatively smooth surface on the bathymetry (Fig. 2a,b). These channels follow the steepest slope. Some of them clearly connect with the coast. They can be identified unambiguously as erosive canyons, probably filled with material derived from land erosion. Their high sonar backscatter implies that their surface is covered by coarse-grained sediments at the scale of the sonar wavelength (around 10 cm). To the east, the NSB is bounded by a large, smooth zone that shows bathymetric and sonar backscatter characteristics similar to that of the sedimentary channels. This area, referred to as the NE Sedimentary Zone (Figs. 2 and 3), appears to be an undisturbed well-developed region of sedimentation.

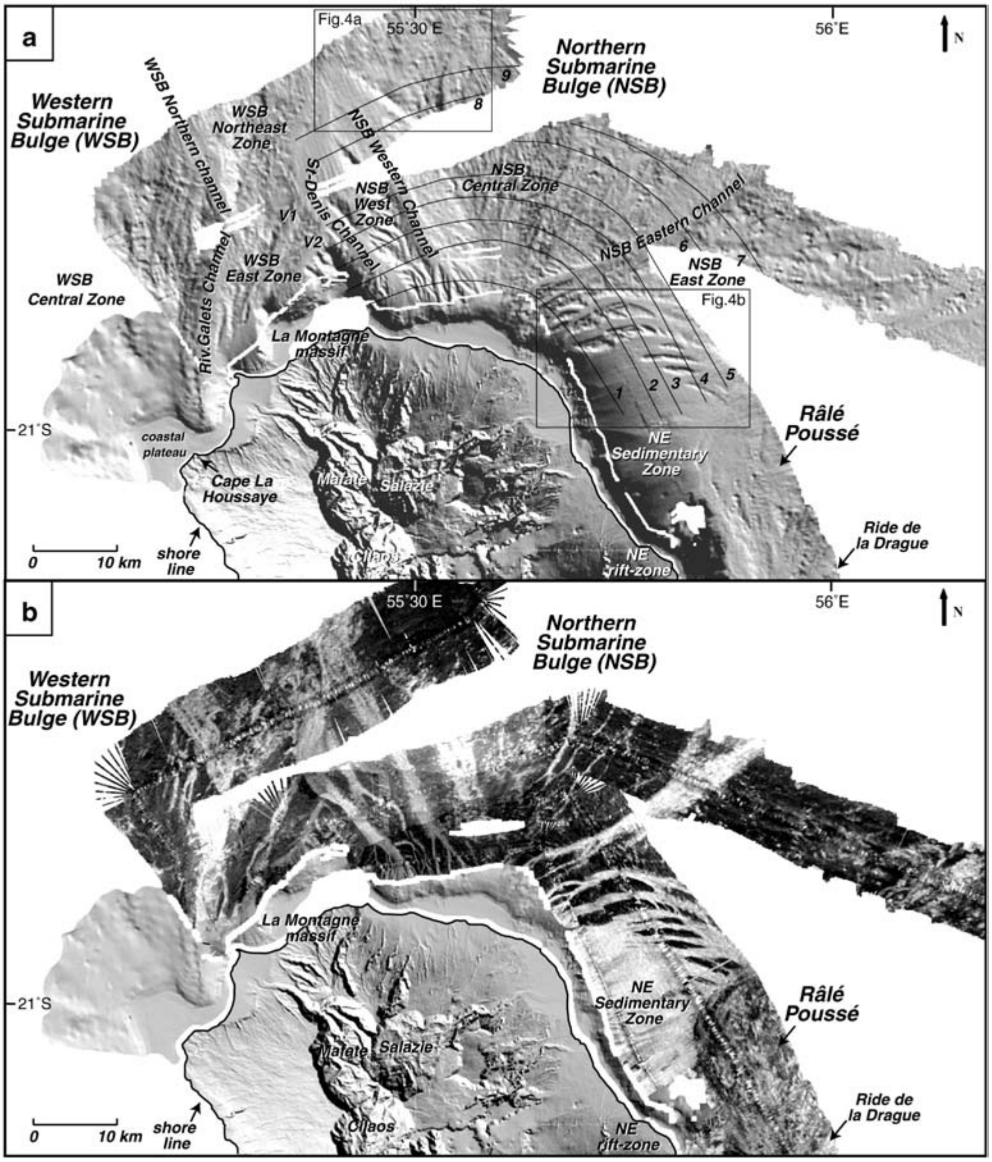


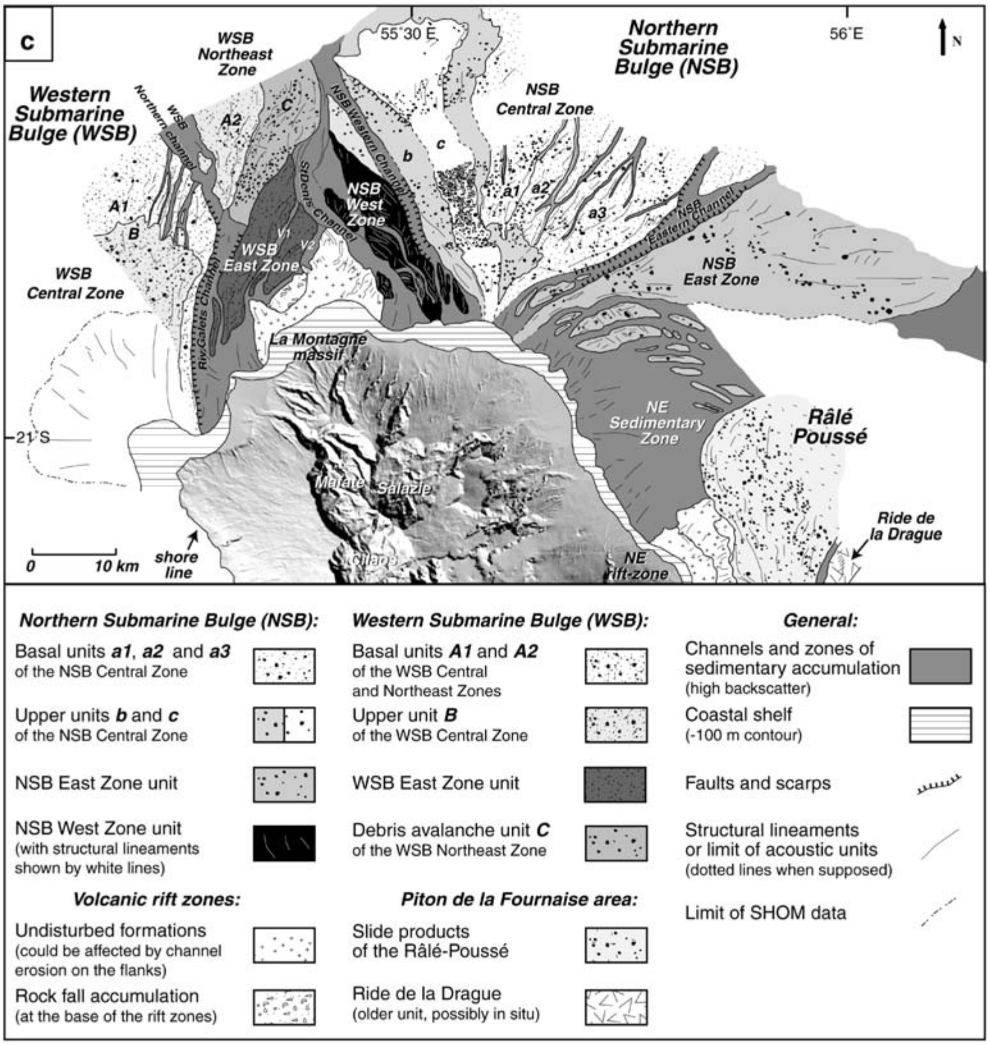
Fig. 2 Views of the northern zone of Reunion Island edifice. (**a**) 100-m-gridded DTM with *shaded-relief overlay* (apparent illumination from the southwest). *Solid lines* numbered from 1 to 9 correspond to bathymetric profiles on Fig. 3. (**b**) 25-m-gridded acoustic image mosaic merged with *shaded-relief map* of the coastal and subaerial parts of the island (apparent illumination from the southwest). *Black* is low backscatter and *white* is high backscatter. The image is a mosaic of intersecting swathes that have been processed with different methodologies. Thus, there are hue variations unrelated to the nature of the terrains at the northern part of the island. However, the boundaries of the different swathes are easily recognized in the figure. (**c**) Interpretative map showing the main offshore features, based on analysis of the acoustic image and the bathymetry. Discontinuous lines indicate interpolation between the sonar swathes

The NSB can be divided into three main zones delimited by three large channels labeled the NSB Eastern and Western Channels and St. Denis Channel (Figs. 2 and 3). These zones are referred to as the NSB Central, East, and West Zones.

The NSB Central Zone forms the apex of the bulge. It is clearly not a homogeneous structure. On the basis of the bathymetry (Figs. 1, 2a, and 3) and partly the sonar image (Fig. 2b), we distinguish two groups of formations. The surface of the units named *b* and *c* is smoother than that of the units labeled *a* (*a1*, *a2*, and *a3*). Unit *c* occupies the summit of the bulge. On the sonar swathes near the coast, this unit is differentiated from unit *b* by a higher sonar backscatter and a dense speckle pattern. The bathymetry is rather smooth, but some ridges and numerous large blocks can be observed. Downhill on the northern swath, this unit becomes well distinct on the bathymetry. It spreads laterally and forms a fan with steep sided border ridges (Fig. 4a). Spots of high sonar backscatter are associated with protruding blocks. Unit *c* is bordered on its west and east sides by unit *b*. The latter has a bathymetric signature similar to that of unit *c*, but with lower sonar backscatter and fewer bright spots. The units labeled *a1*–*a3* have a rougher surface than units *b* and *c* with numerous ridges and furrows (Figs. 2 and 3); they also are carved by several channels filled with high reflectivity material. Unlike the other channels of the NSB, those of units *a* do not extend to the coast. In detail, we observe lateral variations in the morphology patterns, and we have tentatively distinguished three subunits (*a1*, *a2,* and *a3*) on the basis of the bathymetric signature. It is difficult, however, with the available data, to assess whether unit *a* represents a single unit with lateral variations, or if it is a complex of three or more subunits.

The NSB East Zone covers a large area. On swathes near the coast, it is partly intermingled with the NE Sedimentary Zone, forming ridges protruding from the smooth sediment surface. A total of 17 such ridges can be

Fig. 2 c

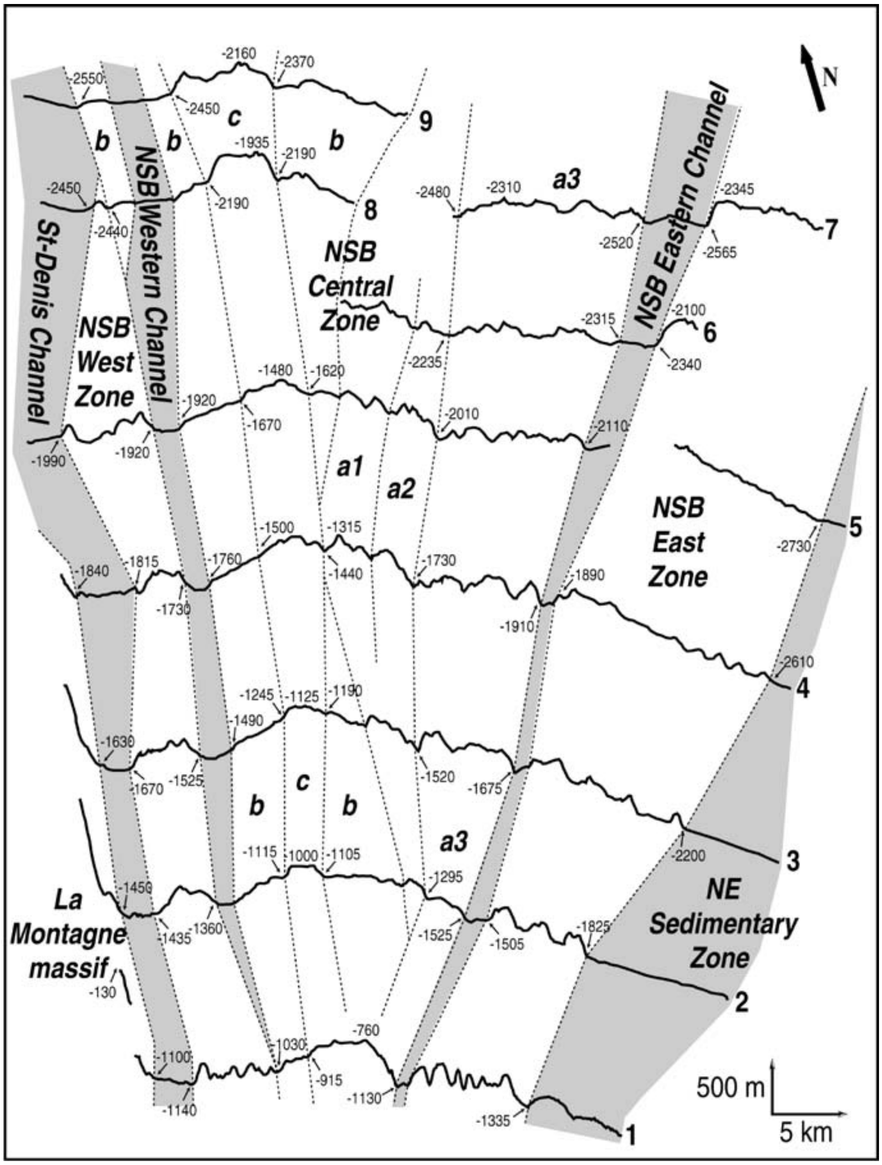


distinguished on the available imagery (Figs. 2b and 4b). They have elongate shapes and are separated by sedimentary channels. Structural lineaments suggest that they are densely fractured. The dimensions of individual ridges can reach 200 m in height, 10 km in length, and 2 km in width. They are probably remnant ridges resulting from submarine erosion. However, one of their remarkable features is that they progressively bend towards the east. This organization is difficult to explain only by erosive processes and we suspect a tectonic origin for their formation. On the swath located farther to the north, sedimentary channels have disappeared, but E–W trending ridges are still conspicuous. The surface is slightly smoother than that of the *a* units.

The NSB West Zone is strongly dissected, showing a dense network of ridges and furrows, some of the latter being filled with smooth sediments. This zone appears to be different from the others, and its surface patterns are indicative of a distinct formation.

The characteristics of the NSB unambiguously indicate a mass-wasting origin. They are obviously different from that of an alluvial fan, which would have bathymetric and backscatter signatures more similar to that of the NE Sedimentary Zone. A submarine volcanic construct would show typical features such as vents and lava flow surfaces. As a whole, the NSB appears to be a huge accumulation of chaotic terrains, comparable to debris avalanche deposits recognized on many submarine flanks of island volcanoes (Fig. 1). It therefore probably results from a series of mass-wasting events that have affected the north flank of the island. The recurrence of mass-wasting events is a common phenomenon on volcanoes. For example, it has been described on the flanks of Mauna Loa (Lipman et al. 1988), Tenerife (Watts and Masson 1995, 2001), La Palma (Urgeles et al. 1999), Montagne Pelée (Le Friant et al. 2003), and on the east flank of Piton de la Fournaise (Labazuy 1991, 1996). The recurrence of landslides on a submarine flank results in a large apron of increasing width between the coastal and distal areas. The landslide complex described by Urgeles et al. (1999) on the southwest submarine flank of La Palma bears many similarities with the NSB such as the presence of large, well-developed, flat-floored channels. Urgeles et al. (1999) suggest that these channels form along topographic lows along the margins of debris avalanche lobes. The location of the channels would therefore delineate the

Fig. 3 Selected bathymetric profiles perpendicular to the structures of the Northern Submarine Bulge (NSB; location is given in Fig. 2a). Negative numbers are depths in meters below sea level. The labels *a1*, *a2*, *a3*, *b* and *c* refer to mapped units shown on Fig. 2c. The *shaded areas* represent channels and zones of sedimentary accumulation



lateral boundaries between successive landslide phases. Urgeles et al. (1999) also note that large channels are only observed in association with relatively old (>100 ka) debris avalanches in the Canary Islands. This observation may be tentatively used for Reunion Island to help establish a relative chronology among the observed landslides phases. In the case of the NSB, the distinct nature of the three main units (the NSB Central, East and West Zones, each separated by sedimentary channels) is consistent with the work by Urgeles et al. (1999) on La Palma. For the NSB Central Zone, units *b* and *c* occupy the top of the bulge and are probably the youngest landslide events. This would explain their more or less pristine surface, whereas the other older *a* units appear more eroded. Furthermore, units *b* and *c* are not eroded by channels. For the NSB East Zone, the orientation of the ridges suggests that the flow of material has been deflected by a pre-existing topographic high in the NSB Central Zone. Accordingly, the NSB East Zone is younger than the *a* units of the NSB Central Zone. By contrast, a landslide origin of the NSB West Zone is not well established. Its surface morphology is different from that of the other units, and it is difficult to assess its nature with the available data. It could be interpreted as a highly eroded, old debris avalanche deposit or as highly fractured slide blocks of constructional origin.

The Western Submarine Bulge (WSB)

The WSB covers the west quarter off the island. It forms a fan-shaped bulge about 25 km wide at the seashore to nearly 150 km on the sea floor. It extends about 50 km offshore (Labazuy 1996). Only its northern portion is partially covered by the new data (Fig. 2).

The northern portion of the WSB shows sonar backscatter characteristics similar to those of the NSB (Fig. 2b), with generally low sonar backscatter values, but also high

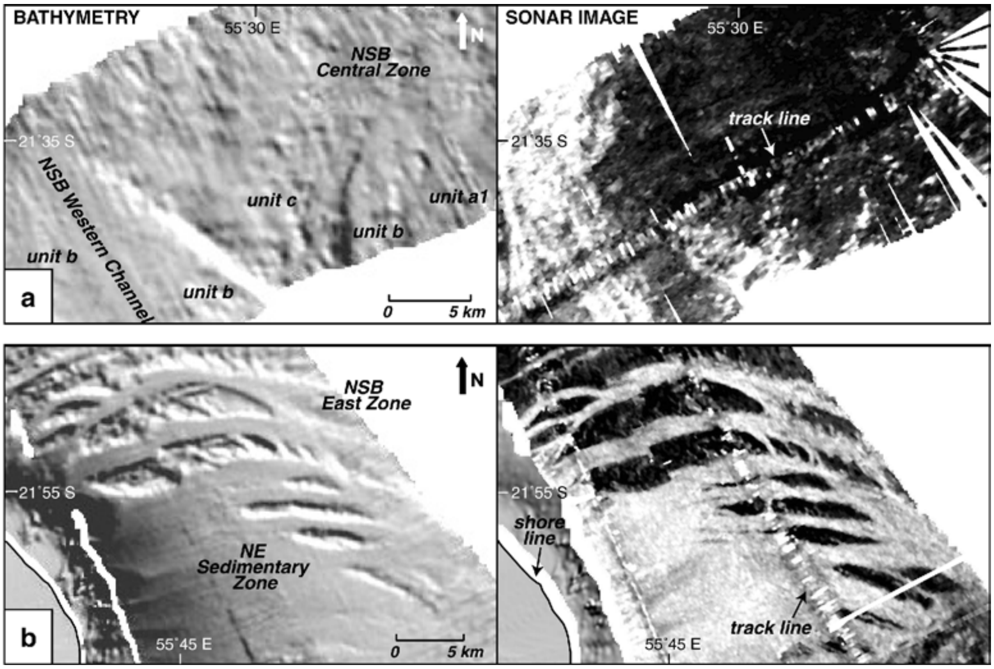


Fig. 4 Detailed view of the bathymetry (*left*) and sonar backscatter (*right*) of selected zones of the Northern Submarine Bulge (NSB; see location in Fig. 2a). Black is low backscatter, and white is high backscatter. (**a**) Northern part of unit *c*. The bathymetry shows a fan-shaped structure with steep-sided border ridges. Protruding blocks are shown by spots of high sonar backscatter. (**b**) Southern part of NSB East Zone. A total of 17 elongated ridges can be distinguished on the imagery. They are extensively fractured and bend progressively towards the east

reflectivity spots underlining the presence of blocks at the surface. The bulge is cut by high-backscat-ter smooth-surface channels, which are easily identified on the bathymetry (Fig. 2a). The two particularly large channels labeled the Rivière des Galets and WSB North-ern Channels, delimit three main zones within the WSB. These zones are referred to as the WSB Central, Northeast, and East Zones (Fig. 2).

Offshore of Cape La Houssaye (Fig. 2a), the northern part of the WSB Central Zone starts with a 100-m-deep, large coastal plateau on which coral reefs have grown. The WSB Central Zone is clearly heterogeneous. The sonar image (Fig. 2b) and the bathymetry (Figs. 1 and 2a) allow us to distinguish, on its northern slope, at least two distinct superimposed types of formations. A basal unit, labeled *A1*, is characterized by a ridge and furrow surface morphology, carved by several channels filled with high reflectivity material. These channels do not connect to the coast but are interrupted by unit *B*, with a smoother surface.

The WSB Northeast Zone is delimited by the WSB Northern channel to the west and the St. Denis Channel to the east (Fig. 2). It can be divided into two juxtaposed units of different bathymetric (Figs. 1 and 2a) and acoustic (Fig. 2b) signatures. The unit labeled *A2* exhibits generally low-sonar backscatter values similar to those of the WSB Central Zone. It forms a prominent triangular structure whose eastern boundary is a NE-elongated ridge. To the east of this ridge, the unit named *C* comprises more chaotic terrains. The acoustic imagery shows a speckle pattern similar to that observed at the surface of the Piton de la Fournaise Râlé-Poussé bulge (Fig. 2b). This pattern reflects the presence of blocks protruding from the surface. The largest blocks visible on the bathymetry (Fig. 2a), are frequently organized in elongated ridges or in lateral lobes. Unit *C* fills the downstream part of the Rivière des Galets Channel and appears to invade the lower part of the St. Denis Channel (Fig. 2).

The WSB East Zone is composed of ridges separated by high backscatter sedimentary channels (Fig. 2). There are two very large ridges, the largest 20 km long and 3 km wide, and smaller ones. The NE boundary of the two largest ridges is marked by a sharp cliff corresponding to the western side of the St. Denis Channel (Fig. 2). The largest channels, labeled V1 and V2, are intersected by the St. Denis Channel, which postdates them, as well as the WSB East Zone ridges. The nature of the WSB East Zone ridges is difficult to establish with the available data. They are probably not homogeneous blocks, but more likely products of old debris avalanches dissected by erosive channels and coated by fine-grained sediments. The geometry of the ridges and the channels is similar to that of the NSB East Zone. The WSB East Zone could thus be debris avalanches deflected by a pre-existing topographic high in the WSB Central Zone.

The WSB (at least its north portion) shares similar acoustic, bathymetric and morphological characteristics with the NSB. It seems unquestionable that the WSB is a huge accumulation of landslide deposits. The WSB thus results from a series of mass-wasting events that have affected the west flank of the island.

A relative chronology can be established among some of the recognized units. The WSB Central Zone shows a sequence of at least two episodes of landslides, with the upper unit *B* overlying unit *A1,* which shows more erosive features. Unit *C* exhibits all the characteristics of a debris avalanche deposit. In particular, its acoustic signature is similar to that of the Piton de la Fournaise Râlé-Poussé bulge (Fig. 2), which is an accumulation of debris avalanche products (Labazuy 1991, 1996). The chronological

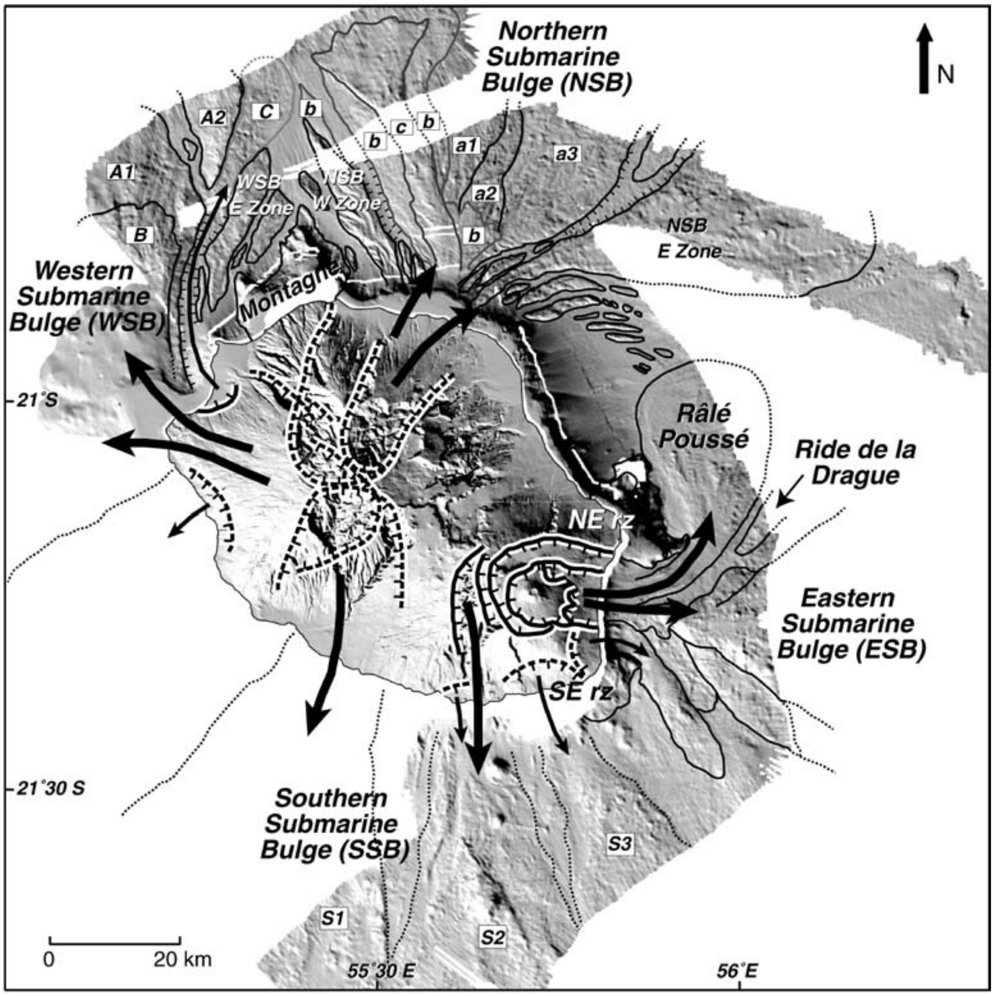


Fig. 5 Interpretative map of the landslides of Reunion Island. The global 100-m-gridded DTM with *shaded-relief overlay* is used as a base (apparent illumination from the southwest). *Large arrows* represent major landslides, *smaller arrows* correspond to smaller events. Structural features are superimposed (*solid lines* when well constrained, *dashed lines* when more speculative). SE rz and NE rz are the Piton de la Fournaise SE and NE rift zones

relationships between the NSB and the WSB cannot be established directly. It is clear that the St. Denis Channel, which separates the two bulges, postdates all identified units in contact with the channel except unit *C*. Similarly, the WSB Northern Channel postdates the erosion channels of unit *A1*, and the Rivière des Galets Channel postdates the units it crosses. Unit *C* debris avalanche was channeled within the Rivière des Galets Channel and spilled into the St. Denis Channel in its lower part. Therefore, unit *C* is probably the youngest slide event of the WSB. The filling of the Rivière des Galets Channel may have formed the WSB Northern Channel. This latter channel follows the steepest slope direction and may have become the new direction of flow for material derived from land erosion after the obstruction of the Rivière des Galets Channel by the debris avalanche deposits of unit *C*. In this case, the WSB Northern Channel formed purely by erosion and would not constitute the lateral boundary of a landslide deposit. Consequently, WSB units *A1* and *A2* may be products of the same mass-wasting event, whose deposits have been separated by an erosive channel.

The Southern Submarine Bulge (SSB)

The presence of the SSB is known from previous bathymetric mapping (Labazuy 1996). The new Atalante data set covers only the eastern fraction of the SSB (Figs. 1 and 5). Therefore, it is not possible to analyze the SSB to the extent of the NSB. Surface morphology and sonar backscatter characteristics of most areas covered by the new data unambiguously show the presence of debris avalanches at the surface. We can recognize at least three units (*S1*–*S3* on Fig. 5). The two easternmost units may be associated with events affecting Piton de la Fournaise, whereas the western unit is more likely related to volcano-tectonic events in the Piton des Neiges area. More data are necessary to make a detailed analysis of the SSB, which appears as a complex assemblage of landslide material.

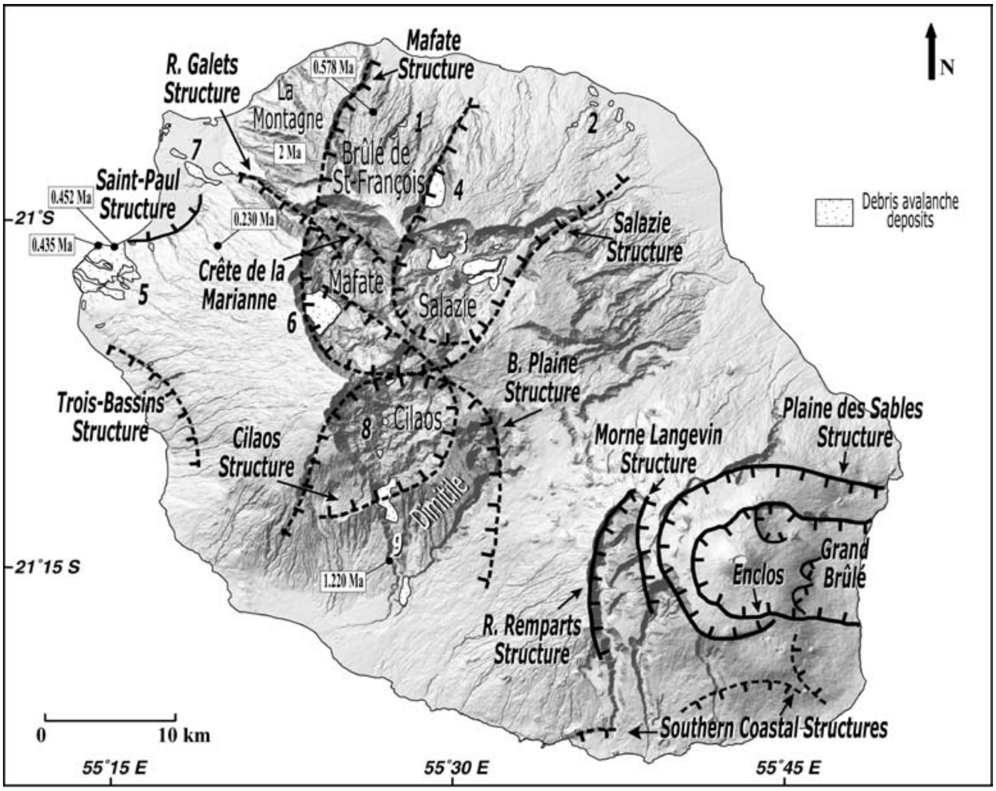


Fig. 6 Inferred source areas of the major landslides of Reunion Island superimposed on a *shaded-relief map* (apparent illumination from the northwest). Well-constrained border faults are shown in *solid lines*, more hypothetical ones in *dotted lines*. Dates are from McDougall (1971). The debris avalanche deposits recognized on land are numbered from 1 to 9. They are located as *1* Ravine des Patates à Durand (Fèvre et al. 2001; Bret et al. 2003), *2* St. Suzanne, *3* Salazie, *4* Rivière des Pluies (Fèvre et al., 2001; Bret et al. 2003), *5* Cape La Houssaye (Bachèlery et al. 1996, 2003), *6* Mafate (Bret et al. 2003), *7* Rivière des Galets (Bret et al. 2003), *8* Cilaos (Maillot, 1999), and *9* Cilaos and Entre-Deux

Discussion

Relationships between emerged and submerged parts of Reunion Island

The available data show that the submarine flanks of Reunion Island are mostly built by accumulations of debris avalanche deposits. This reflects the importance of flank instabilities during the growth of the island in virtually all directions. The headwall of a flank landslide is typically a horseshoe-shaped amphitheatre. However, the headwalls of old landslides are often filled and concealed by subsequent volcanic activity or dismantled by erosion. In Reunion Island, except for the most recent landslide, that of Grand Brûlé in the east, no scars of large, ancient landslides are obvious morphologically. We have searched for remnants of landslide scars in the present-day morphology using a detailed analysis of the DTM and on-land geological observations. We found morphological and geological evidence that allows us to propose source areas for large flank landslides in different areas (Figs. 5and 6). It should be stressed, however, that the precise limits of the inferred source areas are presently poorly constrained by direct geological observations. Indeed, it is very difficult to see and follow geological contacts in this type of environment due to limited outcrop, lateral variations of the volcanic products, erosion, high cliffs, lack of available ages, etc. In addition, it is likely that the landslide events span a very long period of time. The evolution of the volcanic edifices during hundreds of thousands of years creates a complex stratigraphy that is difficult to decipher.

The Piton des Neiges massif

The landslides products of the NSB, WSB, and SSB indicate that flank instabilities have occurred repeatedly during the growth of Piton des Neiges. From our analysis, it appears that most of the inferred headwalls of the landslides generally coincide with the boundaries of the cirques of Mafate, Salazie, and Cilaos.

The Mafate Structure cuts La Montagne massif, which is older than 2 Ma and is filled by younger lava flows which form the present Brûlé de Saint-François (McDougall 1971; Fig. 6). On the basis of morphological criteria, Kluska (1997) proposes that the Brûlé de Saint-François was built ca. 1 Ma. It is therefore reasonable that the dismantling of the eastern part of La Montagne massif and the subsequent filling of the Brûlé de Saint-François can be attributed to a very large landslide of the north flank of Piton des Neiges. The landslide products may form the base of the NSB (units *a* on Figs. 2c and 5). The Mafate Structure would thus correspond to the scar of an event that occurred ca. 1 Ma. On-land fieldwork (Fèvre et al. 2001; Bret et al. 2003) has allowed the recognition of 0.05 km^3 of debris avalanche breccias in the Ravine des Patates à Durand (outcrop 1 on Fig. 6). These deposits constitute subaerial evidence of this ancient destabilization of the north flank of the island.

We propose that the Salazie Structure is the scar of a more recent landslide nested within the Mafate Structure (Fig. 6). Its deposits tentatively may be associated with the NSB East Zone (Figs. 2c and Fig. 5). The depression formed following this slide was partly filled by lava flows of the Oceanite Series and principally by products from the Differentiated Series. On the north flank of Piton des Neiges, the Differentiated Series formations are mainly confined within the inferred limits of the Salazie Structure. This observation argues for the presence of a former depression in this area and indicates that the landslide formed near the end of the Oceanite Series. Some debris avalanche deposits recognized on land may be associated with this landslide event. The St. Suzanne breccias (outcrop 2 on Fig. 6), formerly mapped by Billard and Vincent (1974) as “undifferentiated tuff”, are now interpreted as highly weathered debris avalanche deposits (Bret et al. 2003). They are the continuation of the NSB East Zone (Fig. 5) and thus could be the subaerial deposits of this event. West of these outcrops, drilling data show the presence of breccias that underlie the differentiated lavas along the coast for about 10 km. Newly discovered breccias within the Salazie cirque (outcrop 3 on Fig. 6), are interpreted as debris avalanche deposits and could be the continuation of St. Suzanne outcrops as well as the 1 km^3 of breccias recognized in the Rivière des Pluies (outcrop 4 on Fig. 6; Fèvre et al. 2001; Bret et al. 2003).

The Cilaos Structure (Fig. 6) corresponds to the structure assumed by Lénat et al. (2001) to be a depression filled by lava flows younger than 0.78 Ma. This depression could be the source area of landslides affecting the west flank of the Piton des Neiges, whose deposits are found in the WSB (units *A* and *B* on Figs. 2c and 5). On land, debris avalanche deposits have been recognized in several locations within the inferred limits of the Cilaos Structure. A series of at least four debris avalanches have been recognized by Bachèlery et al. (1996, 2003) in the coastal area near Cape La Houssaye (outcrop 5 on Fig. 6). The lower unit is overlain by a 0.452-Ma-old lava flow (McDougall 1971). It contains hydrothermally altered fragments and is therefore regarded as resulting from a landslide that cut the central part of Piton des Neiges. Its thickness is unknown. We suggest that the scar of this landslide is the Cilaos Structure, although the Crête de la Marianne or Rivière des Galets Structures could also be associated with this event (Fig. 6). The Cilaos Structure intersects and therefore postdates the ca. 1-Ma-old Dimitile. According to Bachèlery et al. (1996), the three upper units of Cape La Houssaye are associated with less significant events younger than 0.435 Ma, which is the age of the lava flow on top of the lower unit, and older than 0.34 Ma (McDougall 1971), which is the age of a lava flow above the Cape La Houssaye debris avalanches. Other breccias, interpreted as debris avalanche deposits, were also found in the Mafate cirque (outcrop 6 on Fig. 6) and in the outlet of the Rivère des Galets (outcrop 7; Bret et al. 2003), but it is difficult to establish whether they are associated with the Cape La Houssaye formations or if they belong to separate landslide events.

Although the new data do not adequately cover the SSB (Fig. 5), it appears that at least one southward-directed major landslide originated in the Piton des Neiges area. Our inferred Bras de la Plaine Structure (Fig. 6) could constitute the source area of this landslide. Breccias identified as debris avalanche deposits have been recognized on land in the Cilaos cirque (outcrop 8 on Fig. 6; Maillot 1999) and in its present outlet (outcrop 9). According to Maillot, these products are younger than 2 Ma and older than 1.2 Ma. Outcrop 8 may be associated to westward as well as to southward-moving landslides, but outcrop 9 is more likely associated with southward-moving landslides. We therefore propose that the southern flank of the island experienced a major landslide between 2 and 1.2 Ma.

The Piton des Neiges massif has thus been affected by successive destruction of its south, west, and north flanks by gigantic landslides before or ca. 1 Ma and of its north flank again near the end of the Oceanite Series at ~0.43 Ma. The geometry of the inferred remnant scars of these destructive episodes suggests a relationship between instabilities of the edifice and the formation of the cirques. Smaller-scale events occurred more recently such as the three last episodes recognized in the Cape La Houssaye breccias or unit *C* of the NSB. Their correspondingly smaller scars are not seen in the present-day morphology because they have probably been eroded or concealed by younger lava flows. However, in the coastal zone, the presence of landslide headwalls is suspected where curvilinear breaks in slope are observed. The Saint-Paul Structure (Fig. 6) is located directly facing the submarine Rivière des Galets channel, which has funneled debris avalanches (unit *C* of the WSB Northeast Zone on Figs. 2c and Fig. 5), and may correspond to the headwall of this secondary landslide. Although recent, it is older than overlying 0.23 Ma lava flows draping the cliff (Fig. 6). The Trois-Bassins Structure could be interpreted in the same manner, but we lack detailed submarine data for the area.

The Piton de la Fournaise massif

Morphological and geological evidence of at least three major collapses of the summit of Piton de la Fournaise have been described (Duffield et al. 1982; Bachèlery and Mairine 1990). They are dated at ~0.15 Ma, 60 ka and 5 ka, the related scarps being the Morne Langevin Structure, the Plaine des Sables Structure and the Enclos Fouqué-Grand Brûlé depression (Fig. 6). Whether these collapses are pure caldera-type collapses, flank collapses, or hybrid collapses is still a matter of debate (Bachèlery 1995; Lénat et al. 2001; Merle and Lénat 2003). However, the submarine data have revealed the presence of ~500 km^3 of landslide material (the ESB) within the continuation of the Grand Brûlé trough, and Labazuy (1996) has interpreted these submarine products as the result of recurrent collapses of the east flank of Piton de la Fournaise. According to him, the central part of the ESB

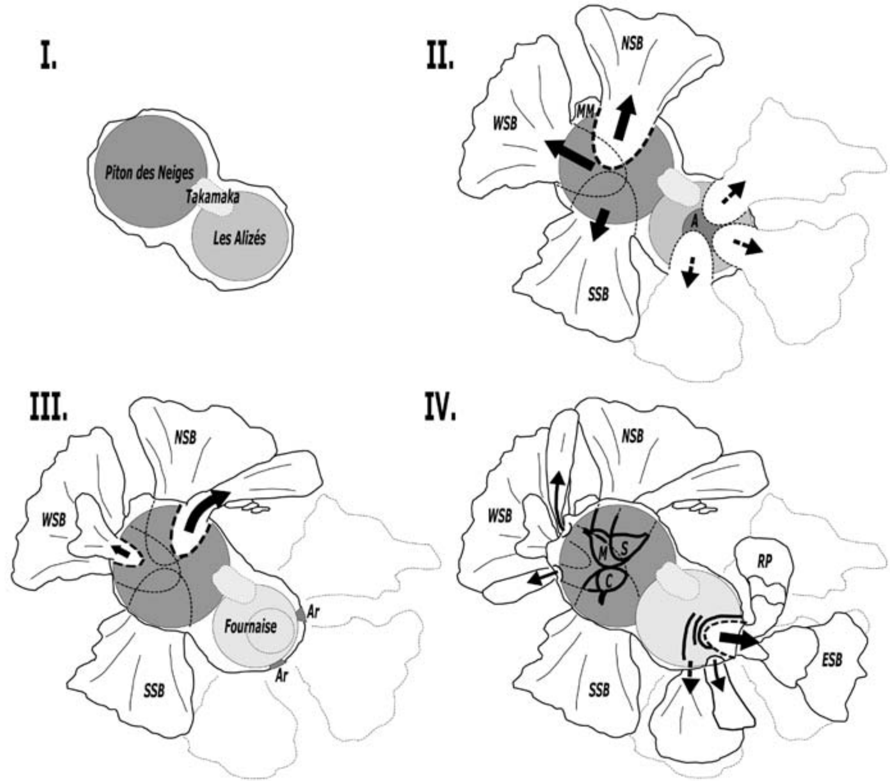


Fig. 7 Simplified sketch of the evolution of Reunion Island for the last 2 Ma. See text for comments. Landslide deposits: *NSB* Northern Submarine Bulge, *WSB*: Western Submarine Bulge, *SSB*: Southern Submarine Bulge, *ESB*: Eastern Submarine Bulge, *RP* Râlé-Poussé bulge. Volcanic complexes: *A* Les Alizés intrusive complex, *Ar* Les Alizés remnants. Other structures: *MM* La Montagne massif; *C* Cirque of Cilaos, *M* Cirque of Mafate, and *S* Cirque of Salazie

is composed of slide blocks, and the Râlé-Poussé was built by debris avalanche deposits originating from the Grand Brûlé area. A debris avalanche that flowed along the southern flank of the ESB, does not appear to have originated from the Grand Brûlé area, but rather from an area south of the Grand Brûlé (Figs. 5 and 6). On the south flank of the massif, several source areas can be inferred for the debris avalanche deposits observed offshore. The Rivière des Remparts Structure (Fig. 6) was interpreted by Bachèlery and Mairine (1990) to be the remnant scar of a 0.3 Ma volcano-tectonic event whose nature was not fully assessed. It may correspond to the source area of some of the debris avalanche deposits observed offshore. In addition, two curvilinear breaks of slope nearer the coast could also be the source areas of submarine deposits (Figs. 5 and 6).

Model of Reunion Island evolution

The limited set of submarine and subaerial geological data do not allow us to develop an exact model for the mass-wasting events during the growth of Reunion Island. However, a synthesis of our new data is important in providing a framework for future investigations. In addition, although some aspects of the synthesis are poorly constrained, it illustrates the major role played by mass-wasting events during the evolution of a volcanic island. The synthesis is shown schematically on Fig. 7.

The subaerial history of the Reunion Island hot spot began ca. 2 Ma ago (Stage I on Fig. 7). Gravity and magnetic studies (Malengreau et al. 1999; Lénat et al. 2001) suggest that the island had two main volcanic foci at this time, Piton des Neiges and Les Alizés volcanoes, and perhaps a third lesser focus, Takamaka volcano. It is probable that these edifices underwent flank mass-wasting, but the associated deposits are probably buried by subsequent activity. However, seismic reflection data (de Voogd et al. 1999) show the presence of debris avalanche deposits lying directly on the pre-volcanic sediments of the oceanic plate at the south of Piton de la Fournaise. They possibly belong to flank landslides from the early stage of Les Alizés volcano.

Stage II on Fig. 7 represents the state of the island ca. 1 Ma. We suspect that Les Alizés volcano had been profoundly affected by mass-wasting events, since virtually no trace of the edifice remains on land beneath Piton de la Fournaise. The major landslides of Piton des Neiges forming most of the NSB, WSB, and SSB are inferred to have occurred during this period. The limited chronological information available suggests that some units of the NSB postdate adjacent units of the WSB.

At the end of the Oceanite Series (~0.43 Ma; stage III on Fig. 7), a succession of smaller landslides occurred on the west flank of Piton des Neiges . On the north flank, a major landslide created the Salazie Structure, which was later filled by products from the Differentiated Series. To the southeast, Piton de la Fournaise started to grow on the remnants of Les Alizés volcano at ~0.53 Ma (Gillot and Nativel 1989).

At ~0.3 Ma (stage IV on Fig. 7), a southward-moving landslide probably formed the Rivière des Remparts

Structure on Piton de la Fournaise. Piton de la Fournaise subsequently experienced eastward-directed landslides constructing the ESB. The work by Merle and Lénat (2003) suggest that volcano-tectonic events leading to the formation of the Morne Langevin, Plaine des Sables and Enclos-Grand Brûlé Structures are hybrid in nature. They involve flank landslides and passive collapses of the summit areas. The two minor landslides at lower elevation on the south flank of Piton de la Fournaise are younger than the Rivière des Rempart slide. During the recent period of Stage IV on Fig. 7, flank landslides ceased on Piton des Neiges. The Saint Paul and possibly the Trois Bassins Structures formed during this period. The depressions resulting from the previous large landslides were gradually filled by lavas from the Differentiated Series. The subsequent formation of the cirques probably results from the combined action of different processes including erosion (Kieffer 1990) and possibly the spreading (van Wyk de Vries et al. 2001; Oehler et al., unpublished data) and subsidence of dense bodies (Lénat and Merle, personal communication). However, their location and shape seem to be controlled by the scars of the previous large landslides.

Origin of landslides

The origin of the destabilization of large portions of volcanic edifices is not fully understood, particularly in the case of gently sloping oceanic shields such as Reunion Island. Several mechanisms have been proposed, including dyke intrusions (Iverson 1995; Elsworth and Day 1999), oversteepening of slopes by the emplacement of new lava flows (Siebert 1984), caldera collapse (Marti et al. 1997), seismicity (Tilling et al. 1976; Lipman et al. 1985), slope dismantling by coastal erosion (Ablay and Hürlimann 2000), and the presence of low-strength layers. Low-strength layers can have different characteristics in volcanic environments including hot ductile cumulates of olivine (Clague and Denliguer 1994), weak volcaniclastic deltas (Duffield et al. 1982), hydrothermally altered zones (Lopez and Williams 1993), hyaloclastites (Garcia and Davis 2001) or marine sediments (Borgia 1994; Merle and Borgia 1996; Borgia et al. 2000). The consequences of the presence of various types of low-strength layers within and below shield-like volcanic islands have been explored by Oehler et al. (2003) using analogue modeling. Their models show that flank landslides can occur passively from deformation of low-strength layers under the volcano load. This suggests that the edifice may become instable in coastal areas because of the presence of weak volcaniclastic deltas. Landslides affecting the central part of the edifice require the presence of an upper weak level within the volcano, such as a hydrothermally altered zone or hyaloclastites, and are more prone to develop when the lower slopes have been destabilized on a volcaniclastic delta. This hybrid mechanism likely explains the largest landslides described in this work. The model of Merle and Lénat (2003) for the Enclos-Grand Brûlé system bears similarities with this process. An important conclusion of the work by Oehler et al. (2003) is that the gravitational spreading of a shield-like volcanic island on marine sediments cannot explain the formation of flank landslides; in the presence of a ductile layer of sediments, the edifice would be affected by subsidence and stretching exclusively. Several authors (de Voogd et al. 1999; Borgia et al. 2000; van Wyk de Vries et al. 2001) have suggested that spreading may have affected Reunion Island and could be still active, but our new bathymetric data do not show obvious spreading-related features (compression ridges, mid-slope benches, etc). Such features, if present, could be concealed by sediments and slide products.

Conclusions

The interpretation of new detailed bathymetric and sonar data, together with the analysis of relationships between the submarine and subaerial geology, provides new information for the evolution of Reunion Island. Approximately 15 mass-wasting events have been identified for both Piton des Neiges and Piton de la Fournaise. These events are only part of the story of the island, since we only have access to the products that have not been buried by subsequent events or by sediments. The dimensions of most of the submarine slide deposits imply large source areas on land. We have attempted to locate these source areas through detailed analysis of the topographic features and of the available geological data. The Piton des Neiges area was affected by several generations of landslides in different directions. The location of the postulated main source areas suggests that the formation of the cirques was influenced by the imprints of the landslide scars. The eastward-directed landslides of Piton de la Fournaise were already known, although some uncertainties remain for the exact source areas of the older deposits. Our work reveals the presence of southward-directed landslides on the volcano's south flank. Their source areas are difficult to recognize in the present surface morphology, although some topographic features suggest the presence of headwalls faults which are partly eroded and buried by subsequent volcanic activity. In contrast, the submarine northern flank of Piton de la Fournaise (or eastern flank of Piton des Neiges) is remarkably smooth and constitutes a large zone of sedimentary accumulation.

The occurrence of large sector collapses during the growth of oceanic volcanoes has been well documented during the last two decades, in particular for Hawaii and Canary Islands. The deposits documented off Reunion Island appear to result mainly from debris avalanche-type events, as is the case for the Canary Islands (Urgeles et al. 1999). No slump comparable with that of Hilina on the south flank of Kilauea volcano in Hawaii is observed on the submarine flanks of Reunion Island. The origin of the huge mass-wasting phenomena is still a matter of debate. The presence of low-strength layers within or below the edifices is essential. On the basis of the analogue modeling results from Oehler et al. (2003), we believe that the presence of weak horizons within the Reunion Island edifice (volcaniclastic deltas, hydrothermally altered zones, and hyaloclastites) were the main causes of large landslides.

Mass-wasting events cutting huge portions of a volcano must play a major role in its construction, magmatic evolution, and eruptive mechanisms. The study of the relationships between the largest mass-wasting events and the evolution of volcanoes remain poorly understood but could now be addressed in the case of Reunion Island. Fuller coverage of the submarine flanks, more geological data, and more sophisticated models are required to understand the evolution of this large hot-spot volcanic system.

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