Structure and morphology of the submarine flank of an active basaltic volcano : Piton de la Fournaise (Reunion island, Indian Ocean)

Réunion
Piton de la Fournaise
Seabeam
rift zones
landslides

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Received 15/10/89, in revised from 08/06/90, accepted 14/06/90.

ABSTRACT

In 1984, a Seabeam bathymetric survey and the measurement of the gravity and magnetic fields of the submarine east flak of Piton de la Fournaise were carried out with R/V *Jean Charcot*.

Piton de la Fournaise, one of the most active volcanoes in the world, is a basaltic shield volcano which occupies the southeastern thirdt of Réunion Island in the southwestern Indian Ocean. Most recent volcanic activity occurred within the youngest caldera and along two volcanic rift zones, which trend northeast and southeast and extend beyond the seashore. The Enclos caldera is breached on the east, where it merges with the Grand Brûlé trough. The northern and shouthern boundaries of this latter depression are two sub-vertical ramparts 100 to 300 metres high; to the west it is limited by a steeply dipping area (The Grandes Pentes), whereas to the east it continues beneath the sea. The Grand Brûlé structure has been interpreted as a slide of the unbuttressed seaward flank of Piton de la Fournaise, the Grandes Pentes area being the headwall of the slide faults.

Three main types of volcanic or volcano-tectonic features have been identified on the Seabeam map, as follows :

• The NE and SE volcanic rift zones of Piton de la Fournaise do not extend more than about five kilometres offshore. Unlike typical Hawaiian rift zones, which form narrow (2-4 km) ridges extending tens of kilometres from the summit, the active rift zones of Piton de la Fournaise widen downslope, attaining more than 10 km in width at their submarine front.

• The submarine extension of the grand Brûlé depression is larger than the subaerial portion. The entire structure forms a 7 km × 24 km scar bounded by two ramparts to the north and south. The slumped material may have moved as a debris flow, forming a large talus downslope of the slide. However, the submarine counterpart of the southern area of the Grand Brûlé seems to comprise a slumped block.

• The third prominent feature is a conspicuous topographic high that occupies almost the entire centre of the surveyed zone. The surface of this "east flank submarine plateau" generally

dips gently (2-3°), and its north and south flanks are extensively cut by landslides. Cone-like reliefs of variable dimensions are observed on the plateau and further to the east. Three hypotheses have been examined to account for the origin of this plateau :
• remnant flank of an ancestral Fournaise volcano associated with a large buried intrusion found by drilling beneath the Grand Brûlé;
• distinct volcanic massif;
• material of a huge landslide.
The latter hypothesis has been confirmed. The geophysical data shown that the western part of this submarine plateau is associated with a moderate positive gravity anomaly and with a magnetic anomaly; this confirms that, as suggested by the bathymetric analysis, this part of the plateau is relatively coherent. Conversely, the eastern portion of the plateau appears to be poorly magnetized and composed of low-density material, probably chaotic and derived from landslides.
These results show that the history of Piton de la Fournaise is characterized by very large episodes of landsliding.

Oceanologica Acta, 1990. Volume spécial **10,** Actes du Colloque Tour du Monde Jean Charcot, 2-3 mars 1989, Paris. 211-224.

RÉSUMÉ

Structure et morphologie du flanc sous-marin d'un volcan basaltique actif : le Piton de la Fournaise (Ile de la Réunion, Océan Indien).

En 1984, un levé bathymétrique Seabeam, ainsi que des levés gravimétrique et magnétique, ont été réalisés sur le flanc sous-marin oriental du Piton de la Fournaise, à bord du Jean Charcot.
Le Piton de la Fournaise est l'un des volcans les plus actifs du Monde. C'est un bouclier basaltique qui occupe le tiers sud-est de l'île de la Réunion dans le sud-ouest de l'Océan Indien. Son activité se concentre à l'intérieur de sa plus récente caldéra (Enclos), et le long de deux rift zones volcaniques qui s'orientent vers le nord-est et le sud-est, et se poursuivent en mer. La caldéra de l'Enclos est ouverte vers l'est où elle rejoint la dépression du Grand Brûlé. Les limites nord et sud de cette dernière sont deux remparts sub-verticaux de 100 à 300 m de hauteur; à l'ouest, elle est limité par une zone à fortes pentes (les Grandes Pentes), et à l'est, elle se poursuit en mer. La structure du Grand Brûlé a été interprétée comme une structure de glissement d'un flanc libre du Piton de la Fournaise, la zone des Grandes Pentes représentant la zone amont des failles de glissements.
Trois principaux types de structures volcaniques, ou volcano-tectoniques, ont été identifiées sur la carte Seabeam :
• Les rifts zones NE et SE du Piton de la Fournaise ne se poursuivent pas au-delà d'environ cinq kilomètres au large. Contrairement aux rift zones hawaiiennes typiques, qui forment des rides étroites (2-4 km) s'étendant jusqu'à des dizaines de kilomètres du sommet, les rift zones actives du Piton de la Fournaise s'élargissent vers l'aval pour atteindre une largeur supérieure à 10 kilomètres à leur extrémité sous-marine.
• L'extension sous-marine de la dépression du Grand Brûlé est supérieure à sa partie sub-aérienne. L'ensemble de la structure forme une cicatrice de 7 km × 24 km, bordée par deux remparts, au nord et au sud. Le matériel impliqué dans le glissement peut s'être déplacé sous la forme d'une coulée de débris qui formerait le relief observé en aval. En revanche, la partie sous-marine correspondant à la partie sud du Grand Brûlé semble composée par un bloc glissé.
• La troisième structure proéminente est un relief important qui occupe pratiquement toute la partie centrale de la zone étudiée. La surface de ce «plateau sous-marin du flanc est» présente une pente générale faible (2°-3°) vers l'est; ses flancs nord et sud sont profondément affectés par des glissements. On observe des reliefs coniques, de dimension variées, sur le plateau et plus à l'est. Trois hypothèses ont été examinées pour interpréter ce plateau :
• reste du flanc d'un ancien volcan associé au complexe intrusif découvert par forage dans le Grand Brûlé;
• massif volcanique distinct;
• matériel provenant d'un ou plusieurs glissements d'amplitude considérable.

C'est cette dernière hypothèse qui est retenue. Les données géophysiques montrent que la partie occidentale du plateau sous-marin est associée à une anomalie gravimétrique positive d'amplitude modeste, et à une anomalie magnétique; ceci renforce l'idée, basée sur l'analyse de la bathymétrie, que cette partie représente un bloc relativement cohérent. A l'inverse, le reste du plateau sous-marin est faiblement magnétique et composé de matériel à faible densité; il s'agit probablement de matériel dont la structure a été désorganisée dans les glissements.
Ces résultats montrent que l'histoire du Piton de la Fournaise a été marquée par de grands épisodes de glissements.

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INTRODUCTION

La Reunion, a volcanic island located in the western Indian Ocean in the Mascarene Basin, lies southwest of, and is aligned with two other volcanic features, the Mascarene Plateau and Mauritius Island. A hot-spot origin proposed for this volcanic chain (Duncan, 1981; Morgan, 1981) is strongly supported by a recent interpretation of geoid anomalies (Bonneville *et al.,* 1988).

The island (Fig. 1) is elliptical in shape (50 km × 70 km) with a NW-SE elongation, rising a nearly flat ocean floor at a depth of more than 4000 m. At the level of the surrounding sea floor, its base dimensions are 200 km to 240 km.

The bathymetry around Réunion island remained poorly known until 1983 (Fisher *et al.,* 1967; Schlich, 1982; Bachèlery and Montaggioni, 1983), when a map of the submarine slopes of the island made by the TAAF (Terres Australes et Antarctiques Françaises) R/V *Marion Dufresne* with conventional bathymetric tools, was published (Averous, 1983) (Fig. 1). This survey was composed of radial profiles regularly spaced every 5° around the islan (except in the north where spacing was 10°) This distance between profiles was about 2 000 m near the coast and 6 000 m at a distance of 40 km offshore.

In 1984, as part of the programme "Tour du Monde du Jean Charcot", a detailed survey of the bathymetry (Seabeam) and of the gravity and magnetic fields was carried out on the east flank of Réunion. This project, named "Fournaise 1", was intended to study the structure of the submarine portion of the active volcano Piton de la Fournaise.

The scope of the present paper is to provide an initial synthesis of interpretations of the data from "Fournaise 1" which have been published separately (Lénat *et al.,* 1989a, Rousset *et al.,* 1987, Lénat and Galdéano in Lénat, 1987).

GEOLOGICAL FRAMEWORK

Réunion island is composed of two volcanoes : Piton des Neiges, which occupies the northwestern two-thirds of the

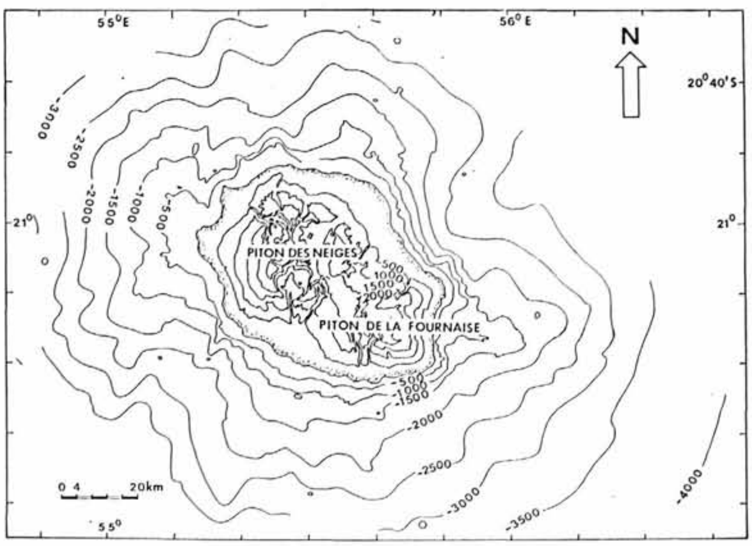


Figure 1

General bathymetry and topography (500 m contour interval) of Réunion island. The bathymetric data are taken from the 1982 R/V *Marion-Dufresne* survey (Averous, 1983).

Carte bathymétrique et topographique générale de l'île de la Réunion (intervalle des contours : 500 m). Les données bathymétriques sont tirées de la campagne de 1982 du N/O *Marion-Dufresne* (Averous, 1983).

island and is a dormant volcano; Piton de la Fournaise; which began to erupt more than 5×10^5 years ago (Mac Dougall, 1971; Gillot and Nativel, 1989), and remains one of the most active volcanoes in the world.

Chevallier and Bachèlery (1981) proposed the existence of four main stages in the evolution of Piton de la Fournaise, the stages being separated by the collapse of three calderas. Constraints on the dimensions and limits of these more or less concealed calderas have been establishes by further studies, and the existence of a fourth caldera has been recognized (Lénat, 1987: Bachèlery and Mairine written com., 1989). The youngest caldera (called "Enclos Fouqué" or, more commonly, "Enclos") probably formed less than 5000 years ago (Bachèlery, 1981). The interpretation of the calderas has been challenged by Duffield *et al.*, (1982) who suggested that the curved rim considered by Chevallier and Bachèlery to be the rims of the two older calderas might in fact be headwall faults of huge landslide blocks of the eastern free flank of Piton de la Fournaise (as opposed to the western flank buttressed on Piton des Neiges volcano). Obviously, the problem of the origin of the caldera-like features is not yet fully resolved, and the submarine survey may provide crucial data to interpret these structures.

Present activity is controlled by a magma reservoir located at a shallow depth (1-3 km – Lénat, 1987) beneath the central cone built in the Enclos. The greatest density of eruptive fissures is found on and around this central cone. On the floor of the Enclos the fissures cluster in two rift zones that continue outside the caldera, curving to the NE and the SE respectively and forming two constructional ridges that widen downslope. Eruptions along these structures outside the caldera are not frequent, averaging two per century during historic times (as compared to an average frequency of one eruption every 14 months in the central area during the recent historic period – Lénat and Bachelery, 1988 –). The last two occured in 1977 on the NE rift zone (Kieffer *et al.*, 1977) and in 1986 on the SE rift zone (Delorme *et al.*, 1989). The relatively large development of the two rift zones outside the Enclos, as compared to their segments inside, indicates that they are long-lived structures that existed before formation of the Enclos.

The Enclos is breached on the east (Fig. 2), where it merges with the Grand Brûlé trough. The northern and southern boundaries of this depression are two sub-vertical ramparts 100 to 300 metres high; to the west it is limited by a steeply dipping area, extensively draped by recent lava flows, called Grandes Pentes (= Steep Slopes). The Grand Brûlé structure is interpreted as a slide (Vincent and Kieffer, 1978). The Grandes Pentes area is interpreted as zone of headwall scarps of gravity faults.

A 3 000 m-deep geothermal exploration hole was drilled in 1985 (Rançon *et al.*, 1989), near the coast within the Grand Brûlé. The hole is situated on a large positive gravity anomaly. The drilling encountered a large intrusive complex (mainly gabbro and dunite) at – 832 m below sea level. The shape of this complex had been established by gravity models (Rousset *et al.*, 1987 and 1989). It is a NS elongated structure about 12 km long and 6 km wide, centered near the coast in the middle of the Grand Brûlé area. It does not extend beneath the presently active centre of Piton de la Fournaise to the west, and no more than 3 km beyond the coast to the east.

The low temperature measured at the bottom of the 3 000 m-deep hole (140°C) indicates that this intrusive

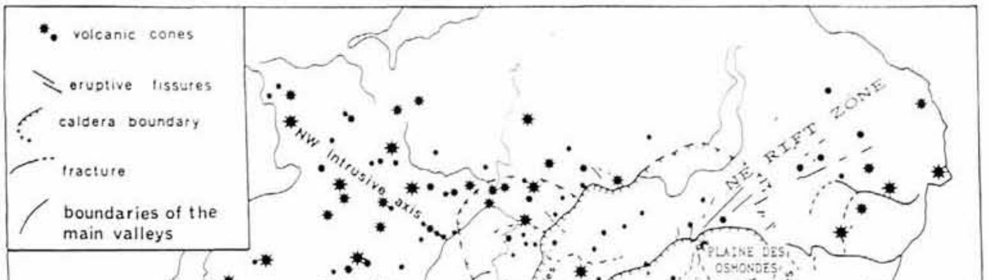


Figure 2

Map of Piton de la Fournaise showing main structural and volcanic features.

Carte montrant les principales structures du Piton de la Fournaise.

complex is not recent. The presence of this large intrusive complex at such a high level in the island suggests that it was a magma reservoir associated with an ancient volcano which is no longer visible at the surface. Similar intrusive stoks have been observed, and their extension mapped by gravity (Puvilland, 1986), in deeply eroded areas of Piton des Neiges volcano. By analogy with active basaltic volcanoes (for example Mauna Loa and Kilauea in Hawaii or Piton de la Fournaise), we can assume that such a magma reservoir was no more than one or a few kilometres deep. Hence we speculate that remnants of the old overlying volcano, which we call "paleo-Fournaise", could still be found despite erosion and possible large subsisdence of the area. The eastern submerged flank should be especially favourable to the preservation of remnants of the ancestral Fournaise, because constructional activity of Piton de la Fournaise was probably less there.

Above the intrusive complex, the lithology comprises several sequences of subaerial and submarine flows. The presence of subaerial flows down to – 718 m below the sea level indicates large subisdence of the area. This downward movement can tentatively be explained by flexure of the lithosphere under the load if the island, or by seaward sliding of large blocks of the eastern flank of the volcano.

According to this geological framework, the main objectives of the survey were :

- to study the offshore continuation of the two volcanic rift zones;
- to study the offshore continuation of the Grand Brûlé structure;
- to seek structures unknown at the surface.

Figure 3 shows the routes of the ship during the survey.

BATHYMETRIC AND GEOPHYSICAL DATA

Bathymetric-topographic map

In order to obtain a view of the whole volcano, and to permit three-dimensional perspective representations, we have created at digital terrain model encompassing the subaerial and submarine parts of the volcano :

- The subaerial topography comes from the 1/50 000 map published by the Institut Géographique National. During the cruise, it was observed that the geographic coordinates of the existing map of Réunion island were not compatible with the reference (WGS 72 ellipsoid) used in navigation. A check made later in a harbour at the south of the island (Saint Pierre) showed that the island had to be shifted 0.37′ towars the west (0.64 km) and 0.75′ towards the south (1.39 km) to be in agreement with the offshore data.
- Most of the bathymetry is, of course, based on the Seabeam data from "Fournaise 1". The positioning of the ship was determined using the "Transit" system; between fixes (up to several hours), navigation was by dead reckoning. This resulted in navigational errors that were detected at track crossings and required adjustements of up to one-and-a-half kilometres for some profile segments. In the surveyed zone (Fig. 3), the Seabeam swaths do not overlap. Between the mapped swaths, the bathymetry was hand interpolated. A detailed map of the Seabeam survey has been presented elsewhere (Lénat *et al.*, 1989a).
- The bathymetry near the seashore, at the northeast of the island, was completed with detailed conventional bathymetric data provided by the "Service Hydrographique et Océanographique de la Marine" and contoured by J.P. Mazé (IFREMER).

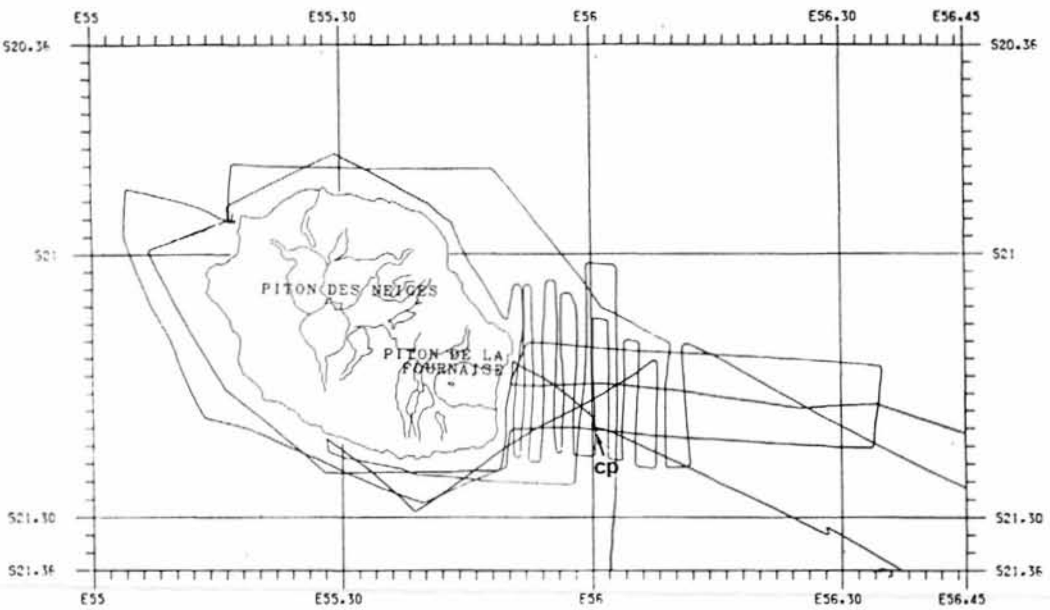


Figure 3

Map showing R/V Jean Charcot tracks during "Fournaise 1" survey. CP is the site of bottom pictures.

Carte des routes suivies par le N/O Jean Charcot lors de la campagne "Fournaise 1"; CP : le site de prise de vue des photographies du fond.

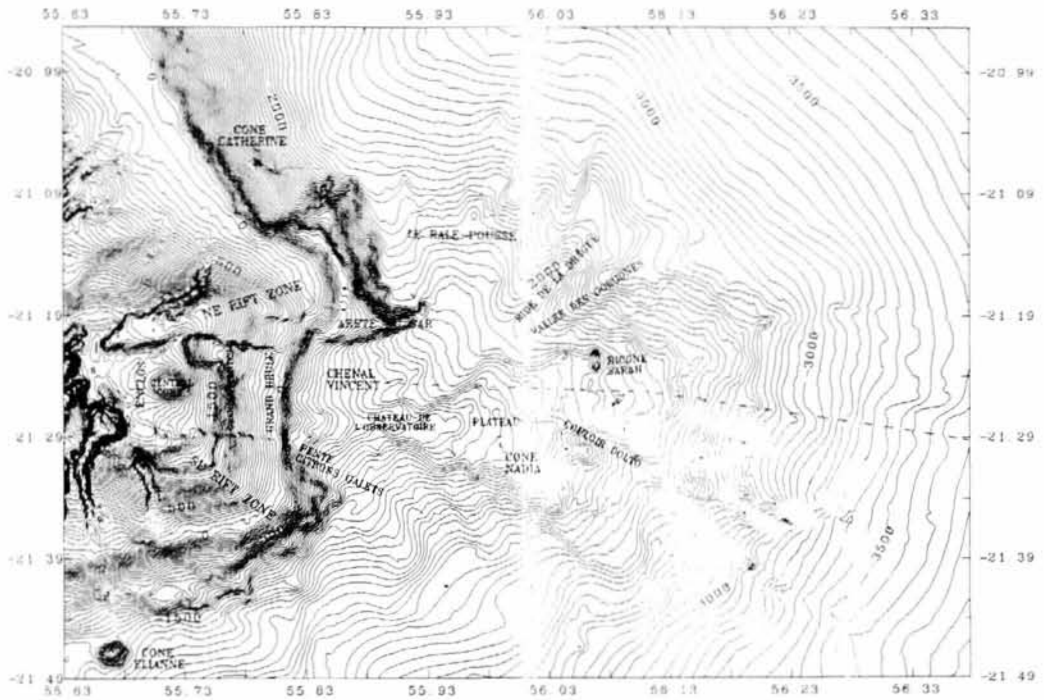


Figure 4

Topographic and bathymetric map of Piton de la Fournaise. This map, a compilation of several sets of data (see text), has been drawn by automatic contouring of the topographic grid computed for the area (square mesh of 0.0025°). The bathymetry is mostly based on Seabeam data. The shiptrack corresponding to the profile of Figure 9 is shown by a dashed line. Names have been given to the most prominent features of the undersea domain.

Carte topographique et bathymétrique du Piton de la Fournaise. Cette carte résulte de la compilation de plusieurs jeux de données (cf. texte). Elle a été tracée automatiquement à partir de la grille du modèle numérique de terrain topographique calculé pour cette zone (mailles carrées de 0.0025° de côté). La bathymétrie est principalement basée sur les données Seabeam. Le trajet du bateau correspondant au profil de la figure 9 est indiqué par une ligne en traits discontinus. Des noms ont été attribués aux reliefs sous-marins les plus marquants.

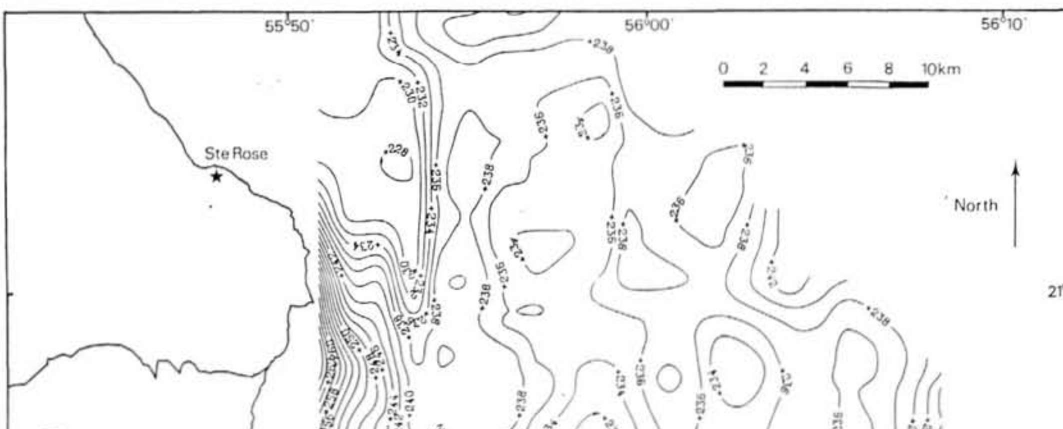


Figure 5

Bouguer anomaly map for a 2.7 gcm^{-3} density. Contour interval : 2 mgal. The regional field is assumed to lie around 238 mgal. (after Rousset et al., 1987).

Carte de l'anomalie de Bouguer (densité 2.7 gcm^{-3}). Intervalle entre les contours : 2 mgal. le champ régional est estimé être de l'ordre de 238 mgal. (D'après Rousset *et al.*, 1987).

• Outside the areas covered by the Seabeam bathymetry, on the northern, southern and eastern edges of the map, the bathymetry was taken on the general bathymetric map of the island (Averous, 1983).

The 100 m interval contour curves of the resulting map were digitized and a grid of regularly spaced data was then calculated (square mesh of 0.0025°) to draw the map of Figure 4, by automatic contouring, and the perspective views presented below.

Gravity and magnetic maps

The processing of the offshore gravity data is described in Rousset *et al.*, (1987). We show on Figure 5 the map of the computed Bouguer anomaly for a density of 2.7. The map clearly indicates that the dense body which creates a large positive anomaly on land (Gérard *et al.*, 1980; Rousset *et al.*, 1989) does not extend further than 1 to 3 km offshore. The other main feature of the map is the presence of a relative gravity low in the centre of the surveyed area. This corresponds approximately to the plateau area and can be interpreted (Rousset *et al.*, 1987) as a 1 km thick layer with a density of 2.5. This model is consistent with an interpretation of the plateau and adjacent areas in terms of material deriving from landslides.

The total field magnetic anomaly map (Fig. 6) has been compiled by Galdéano *et al.* (in Lénat, 1987, 124-128). According to the magnetic latitude of Réunion island, the corresponding anomaly for a given normally magnetized body is composed of a northern magnetic high and a southern magnetic low. The body is located roughly above the magnetic high and the northern zone of the magnetic low.

A north-south succession of three reversed anomalies appears on the map. A preliminary model indicates that the two anomalies which lie in the continuation of the Grand Brûlé and the southern rift zone can be mostly attributed to the rocks of the topographic reliefs. The northern anomaly, which is the more prominent one, has a west-east extension of about 20 km. This anomaly cannot be associated with any surface topographic feature. Therefore, it indicates the presence of a buried structure whose magnetization is probably reversed. A quantitative three-dimensional interpretation of the magnetic data will be carried out together with that of the recent aeromagnetic map of Réunion (Galdéano *et al.*, 1989).

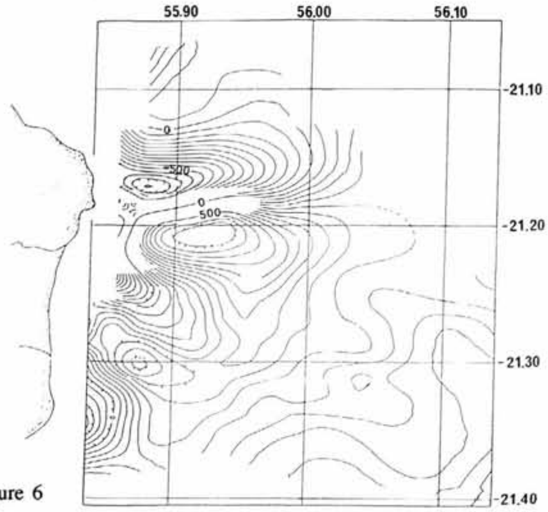


Figure 6

Map of the total magnetic field anomaly at sea level.

Carte des anomalies du champ magnétique total au niveau de la mer.

Description of the bathymetric features

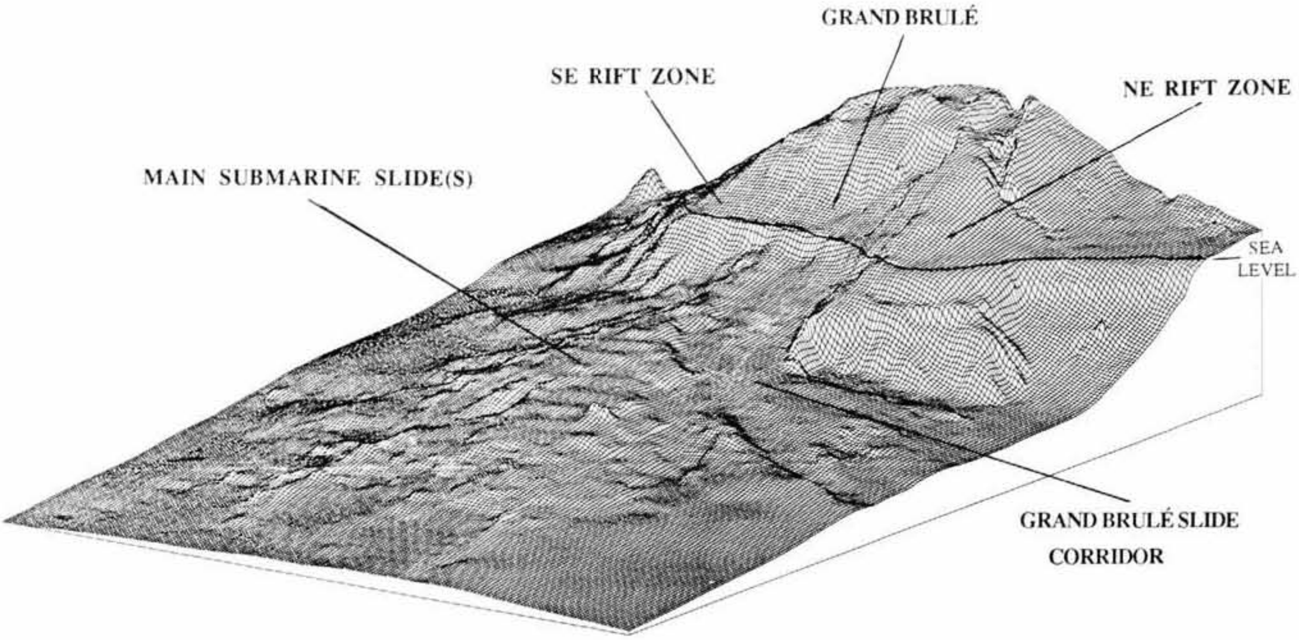
It can easily be seen that the two types of volcanic structure recognized on land (*i.e.* volcanic rift zones and the Grand Brûlé slide) have conspicuous submarine continuations (Fig. 4), and that the plateau and adjacent areas (herein referred to as the "east flank submarine plateau"), constitute an original submarine feature. But on a broader scale, a still more obvious feature is the difference between the subaerial and submarine slopes. Figure 7 shows the average slopes of the area as a function of the elevation. The submarine slopes rise steadily from the ocean floor to about – 1 500 m (O° to about 7.5°), where they start to increase very sharply to a peak value of 24° between about – 500 m and – 100 m. Near the shoreline the slopes are again moderate (~ 7°); they increase to an average value of 15° at higher elevations where the curve become less regular because of the effect of valleys, caldera rims and caldera fillings.

THE NE AND SE VOLCANIC RIFT ZONES

The NE and SE rift zones, which form broad topographic ridges (Figs 4 and 8), are relatively narrower upslope (2 to 3 km) when they diverge from the Enclos but widen downslope, becoming 3 to 5 times wider at the shoreline where they form pronounced coastal promontories. The presence of parasitic vents and cones along these ridges confirms their constructional origin and the observations of the recent eruptions of April 1977 (Kieffer *et al.*, 1977) and March 1986 (Delorme *et al.*, 1986) have confirmed that they behave as Hawaiian type rift zones (*i.e.* they drain magma from the central zone).

These rift zones do not extend beyond a few kilometres offshore. The lateral extension of their submarine counterparts generally fits with the boundaries that could be extrapolated from surface observations (Fig. 4), except for the southern submarine portion of the SE rift zone which shows topographic features over a wider area than might be expected from the surface extension of the present rift zone. The features lying outside the natural continuation of the rift zone may be associated with phenomena affecting the south flank of the volcano (*i.e.* landslides).

The physiography of the submarine part of the NE rift zone is not thoroughly understood. It seems that it could have been disrupted by landslides on its northeastern and southern edges. A flat area around – 500 m to – 600 m suggests that the constructional processes have not been continuous (*i.e.* the upper part would be built on a pre-existing surface).



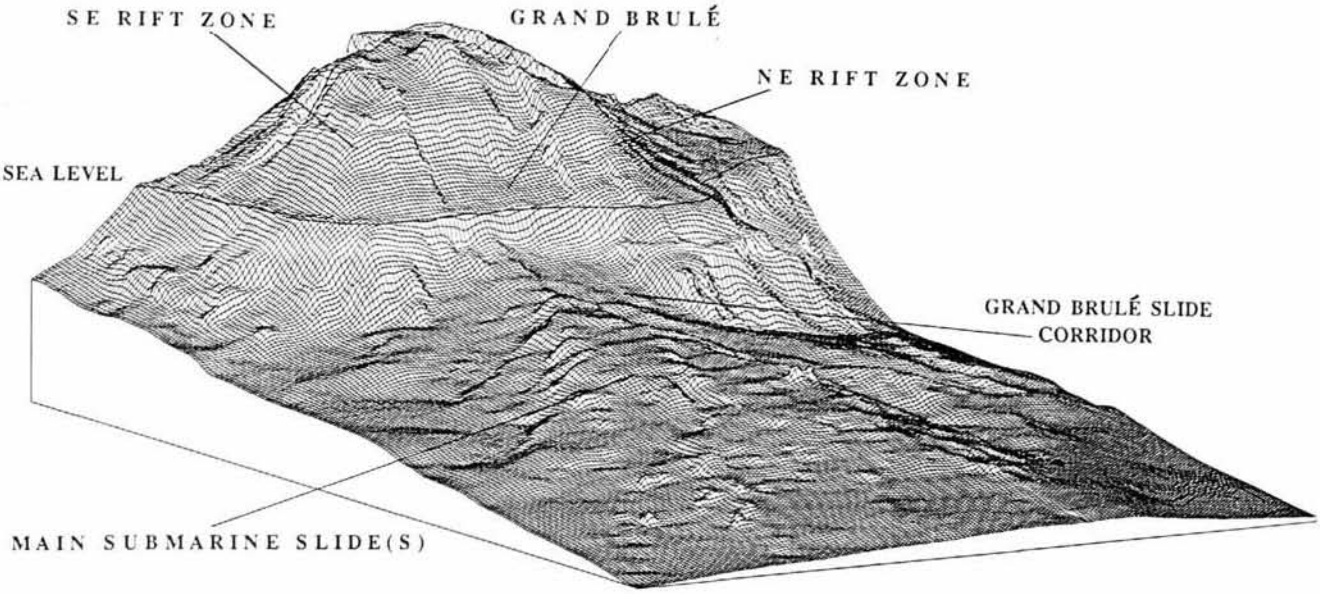


Figure 7

Three-dimensional representations of the subaerial and submarine parts of Piton de la Fournaise, showing the main structural features. (Vertical exaggeration of 3.5)
a : view from the NE.
b : view from the SE.

Représentations en perspectives montrant les principales unités. (exagération verticale : 3.5)
a : vue depuis le nord-est.
b : vue depuis le sud-est.

THE GRAND BRÛLÉ SLIDE

The submarine counterpart of the Grand Brûlé is the 13 km long depression (Chenal Vincent) which trends W-E near the coast, and then curves to the northeast. However, the north and south rims of this corridor do not fit exactly with the subaerial ones.

To the north, the submarine rims seem to connect with the Ravine Constantin, a south-facing rim located 3 km north of the northern rampart of Grand-Brûlé. The ravine Constantin rim, which is partially buried by lava flows, has been regarded as the headwall of a slumped block by Bachèlery and Chevallier (1982).

To the south also, the north-facing submarine rampart is not in line with the subaerial one; it is shifted more than 2 km to the north. The area between these two rims belongs to the "east flank submarine plateau", a structure that will be described below.

Downslope of the submarine corridor, a delta-like feature (Le Râlé-Poussé) seems to be composed of material involved in the slide (Fig. 4).

In the unmapped area close to the coast, interpolation of the bathymetry required that the slopes dramatically increase seaward in this area.

THE EAST FLANK SUBMARINE PLATEAU

This broad topographic high occupies almost the entire centre of the surveyed zone (Figs. 4 and 8).

It has roughly the form of a sector starting from the coast, off the southern zone of the grand Brûlé, and opening eastward with an angle of about 40°. Its surface is subhorizontal, the general slope towards the east is 2 to 3° between about – 500 and – 2 000 m and is composed of subplanar areas separated by steps with a dip of 5° (visible on more detailed maps). Eastward, a larger gradient between about – 2 000 and – 2 500 m apparently marks a structural boundary. In this transition zone the topography is more irregular. Downslope, from about – 3 300 m, the slope is slighter (2°) and the seismic reflection data shows the presence of stratified sediments above the acoustic basement (Fig. 8). Thus the – 3 300 m countour is a boundary between younger terrains with little or no sedimentary cover and older terrains covered by thicker layers of sediments described by Philippot (1984) as detrital and hemipelagic sediments.

The northern and southern flanks of the bulge are extensively scarred by landslides (Fig. 4). Its W-NW part seems to be eroded by the Grand Brûlé slide. On more detailled maps, numerous hills or cone-like reliefs are observed. The dimensions of the individual cones vary from 100 m to nearly 1 km in base and from 20 to 300 m in height. Even on detailed enlarged plots of the Seabeam data, none of them show a summit crater. On the other hand, some 20- to 60-m deep depressions are observed on the plateau, but there are not associated with cones. The cones are either circular or elongated along the local slope. A set of pictures (only 5 because of equipment failure) were taken on the flank of a large cone (Cone Nadia, CP on Figure 3). Both clastic or detrital material and pahoehoe-like flows uncovered by sediments were observed.

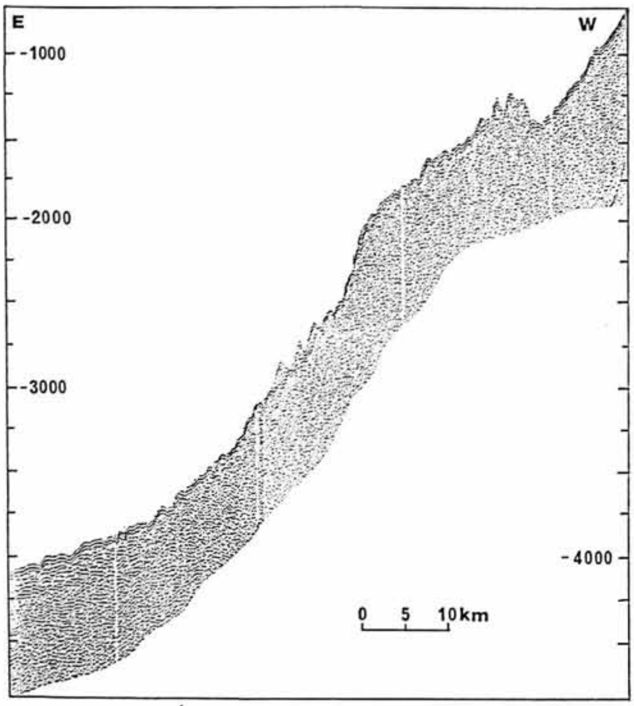


Figure 8

E-W seismic profile. Its location is shown on figure 4. These data illustrate the texture of the surface in the different areas, and show the presence of layered sediments beneath ~ – 3500 m.

Profile E-W de sismique reflexion. Sa localisation est montrée sur la figure 4. ces données illustrent la texture de surface des différentes zones, et montrent la présence de sédiments lités à partir d'une profondeur d'environ – 3500 m.

DISCUSSION

Submarine slopes

The distribution of slopes in the surveyed area of Réunion contrasts with that of the younger segment of the island of Hawaii (Mark and Moore, 1987), although the two localities are considered to be of very similar volcanic construction. In Hawaii, the submarine slopes are significantly higher (about 5°) than they are in the Piton de la Fournaise area, and conversely, the inverse observation can be made on land. However, in both cases, the same dramatic increase of slope occurs in the seashore area. Mark and Moore (1987) propose that "this marked slope change at the subaerial-subaquous transition zone is the result of several processes, primarily volcanic", because on young volcanic coasts erosion and growth of coral reef are minimal. According to these authors, the three main processes involved would be :

- the chilling effect of water that "tends to increase the flow's effective viscosity" and "cause it to thicken or divide into pillowed flow lobes and hence flow a shorter distance, thus steepening the general slope angle";
- "surf action which disrupts flow channels and lava tubes and causes the flow to divide spread and flow a shorter distance over a broader front";

• and a third, and perhaps the most important, process depends on the buoyant effect of water on the propagation of a lava flow. When a flow crosses the shoreline and enters the sea, its effective density drops by 1 g/cm^3. The flow cannot move downhill on the same slope as readily, because gravity exerts less force on it, and so the flow will thicken and spread laterally". "The net effect of these processes that inhibit flow of lava under water is to cause the shoreline to be extended seaward with a gentle subaerial slope and to pile lava up below sea level".

This general explanation seems to be also suitable for Réunion, the general bathymetric map of which (Averous 1983) reveals that similar steep slopes are present almost everywhere around the island near the coast. The difference in submarine slopes between Réunion and Hawaii, at greater depths, have no definitive explanation. A tentative one could be to invoke a difference in the rates of subsidence of the islands (*i.e.* lower rate of subsidence in the case of Réunion would allow the products of the various eruptive and tectonic process to spread further laterally). However, this explanation does not account for the higher subaerial slopes of Réunion.

The volcanic rift zones

The concept of volcanic rift zones has mostly been defined in Hawaii : they are considered as flank-preferential intrusive-eruptive zones that converge at the summit caldera or central zone of a volcano. It has been shown (Fiske and Jackson, 1972) that the orientations of the volcanic rift zones are controlled by the gravitational stresses of the volcanic edifice that are strongly influenced by adjacent volcanoes. They have no regional tectonic significance except for isolated volcanoes whose earliest stages of growth may be affected by the regional stress field. The archetype of volcanic (or Hawaiian) rift zones are those of Mauna Loa and of Kilauea. They are linear or curved ridges, 2 to 3 km wide and tens of kilometres in length. Kilauea east rift zone, for example, is about 120 km long with 70 km being submerged. This off-shore continuation (called Puna ridge) of the Kilauea east rift zone has been thoroughly mapped (Moore, 1971) and studied (Malahoff and Mc Coy, 1967; Fornari *et al.*, 1978; Lonsdale 1989). Although some differences are found between the subaerial and submarine topography, the offshore part basically remains a linear ridge similar to the exposed part. At Piton de la Fournaise, Bachèlery (1981) noted that the preferential NE and SE intrusive zones are not exact analogs of the Hawaii rift zones. If they actually have a similar width in the central area, *i.e.* within or near the caldera, they widen downslope and become more diffuse structures than well-defined Hawaiian rift zones. This suggests that the gravitational stresses become less focused on the lower flanks of Piton de la Fournaise. This distribution, or dilution, of the intrusions in an area about five times wider than the Kilauea east rift zone may explain why the NE and also SE rift zones of Piton de la Fournaise have not developed further than about five kilometres offshore.

Magnetic data suggest that the core of the submarine part of the SE rift zone could be composed of reversely magnetized rocks. If this is the case, the present subaerial SE rift zone would have developed along a significantly older volcanic feature. The magnetic map also shows that the NE rift zone likewise is built above a buried, narrower (3-4 km) and older (apparently reversely magnetized) structure extending for about 15 km eastward from the south of the submarine par of the present NE rift zone. This latter structure has no gravity expression, and its nature remains to be established.

Landslides

THE GRAND BRÛLÉ SLIDE

The origin of the Grand Brûlé slide has been ascribed to the development of gravitational instability of the free flank of Piton de la Fournaise as a result of the dilatation of the central area of the volcano caused by numerous intrusions. This interpretation is largely inspired by the results obtained for Kilauea, whose south flank exhibits similar patterns of block displacement (Swanson *et al.*, 1976; Lipman *et al.*, 1985). About 97 % of the recent eruptions of Piton de la Fournaise have occurred inside the Enclos. Assuming a frequency of one eruption every year-and-a-half (*i.e.*, about the frequency observed during the last fifty years or so – Lénat and Bachèlery , 1988) and the associated emplacement of a feeder dyke 0.5 to 1 m thick for each eruption, we can estimate that the dilatation of the central area should reach several tens of metres per century.

The age of the Grand Brûlé landslide structure is unknown. Nor is it known whether the slumping is a progressive or a sudden process, or whether the observed structure repesents a single episode of sliding or the sum of periodic slides. The Enclos, formed less than 5 000 years ago (Bachèlery, 1981), seems to be intersected by the slump (Fig. 2). If so, the slumping event or events would also be younger than 5 000 years. In fact, field observations of the rims of the caldera and of the rims of the Grand Brûlé indicate that both are about contemporaneous (same degree of erosion and vegetation). This raises the question of a possible correlation between the two events. The unloading of the edifice by the landslide may have induced a pressure disequilibrium between a magma reservoir and the surrounding lithostatic pressure, thus triggering a large eruption that drained the magma reservoir and resulted in collapse of the central area of the volcano. Alternatively, the collapse of the caldera may have triggered the sliding of an already unstable flank. A third hypothesis would be to consider the formation of the Enclos and of the Grand Brûlé as a single event of landsliding. This hypothesis is currently being carefully investigated (Lénat, pers. comm. 1989).

THE SUBMARINE PLATEAU

The origin of this large feature, called the "east flank submarine plateau", was not easy to establish. Three main hypotheses have been considered :

- that is a remnant of the east flank of the ancestral Fournaise volcano whose existence has been speculated from the presence of the large buried complex of gabbro and dunite beneath the Grand Brûlé area (Rançon *et al.*, 1989);
- that is a distinct constructional volcanic massif;
- that is the product of one or more huge landslides.

It is difficult to regard a plateau dipping at only 2 to 3° as the flank of a shield volcano, because the typical slope of such volcanoes is generally two or three times greater (except for Kilauea, see Mark and Moore, 1987). However it should be emphasized that the present slope may be different from the original slope, which erosion and subsidence of the island may have contributed to reduce. An analysis of the subsisdence of the islands of the Hawaii archipelago (Moore, 1987) has shown this subsidence (flexure of lithosphere in response to loading by the growing islands and removal of magma from depth) to be as large as 5 to 8 km, and as fast as 2.4 mm/year for the presently active island of Hawaii. This phenomenon cannot be overlooked in the case of Réunion. The interpretation of the geoid anomalies required a flexure of the lithosphere of the order of 4-5 km beneath Réunion (Bonneville *et al.*, 1988). If the age of the ancestral Fournaise is of the order of 1 m.y ± some hundreds of thousand years (a minimum estimate based on the fact that the large gabbro-dunite intrusive complex is now totally cooled), it can be speculated that the island has subsided since then in response to progressive loading by the modern Piton de la Fournaise volcano. The east flank submarine structure is in the zone where the angle of flexure should be large; hence if this structure is as old as the gabbro-dunite intrusive complex, it has certainly been tilted toward the island. Montaggioni (1978) estimated the recent subsidence rate of Réunion to be 0.03 to 0.05 mm/yr, using coral reef growth rate on the SW coast. These values would be far too low to account for an inferred tilting of several degrees, but it is not a definitive counter argument since it concerns the inactive part of the island and only recent subsisdence.

The second hypothesis would be supported by the presence of numerous cone-like reliefs that could be eruptive vents. The fact that the structure is extensively affected by landslides cannot by regarded as an argument for an old age because the presently active seamount of Loihi, south of Hawaii, has undergone extensive mass wasting on its flanks (Malahoff, 1987; Fornari *et al.*, 1988). However it should be emphasized that no earthquake has been recorded in the area of Réunion by the seismic network of the volcanological observatory (in operation since 1980).

In the case of the third hypothesis, the total material involved in the landslide would be encompassed by an area of approximatively 300 km^2 in surface and 1 to 2 km high (300-600 km^3). The cone-like features could be relatively coherent blocks protruding above the less coherent matrix of the large landslide. Similar blocks were found at the surface of the Alika landslide (Lipman *et al.*, 1988) on the western submarine flank of Mauna Loa volcano (Hawaii).

A key zone may be that which lies offshore the south of the subaerial part of the Grand Brûlé ("Château de l'Observatoire" and adjacent eastern area, Fig. 4), and forms part of the east flank submarine plateau. Since this area lies directly in the continuation of the south part of the Grand Brûlé, it has to be interpreted as a slumped block. Therefore, the east flank submarine plateau could be totally or partially composed of slumped blocks.

Constraints are provided by the gravity and magnetic data. The westernmost 10 km of the submarine plateau corresponds to a magnetic anomaly (Fig. 6). This area is also characterized by a small but significant positive gravity anomaly (Fig. 5). By contrast, the eastern part of the submarine plateau yields a negative gravity anomaly, and no obvious magnetic signature. Therefore these data support the hypothesis that the western part of the submarine plateau corresponds to a relatively coherent block, whereas the eastern part could correspond to much less coherent blocks whose structure has been disrupted by landsliding.

The surface morphology, particularly when observed in 3D representation (Fig. 8), appears to be unambiguously that of a chaotic terrain, such as it would be expected in the case of huge landslides.

Our interpretation of the Grand Brûlé submarine extension, and of the "east flank submarine plateau", in terms of landslides emphasizes the importance of mass wasting in the evolution of Piton de la Fournaise. Volumetric estimates show that the material of the "submarine east flank plateau" (about 600 km^3) cannot be encompassed within the presently visible scar of the east flank (about 60 km^3). Thus, the occurrence of older slides must be assumed to account for the emplacement of this material, but the data of "Fournaise 1" alone does not permit us to address this problem.

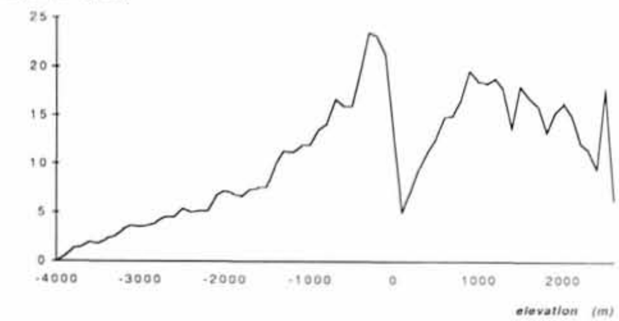


Figure 9

Average slopes as a function of elevation in the surveyed zone. (Slopes computed by fitting a quadratic surface to the 3 × 3 array around each point of the grid used to drawn Figure 4).

Pentes moyennes en fonction de l'altitude dans la zone étudiée. (Les pentes ont été calculées à partir du modèle numérique de terrain sur des fenêtres de 3 × 3).

Although our interpretation is mostly based on topographic features only, and therefore needs to be confirmed and refined by complementary surveys, it appears that two types of landslides can be recognized.

On one hand, the system comprising the submarine corridor -Chenal Vincent) and the inferred zone of deposits (Le Râlé-Poussé) can be assumed to derive from a debris avalanche.

This assumption is based on the presence of a long scar (the corridor), and on the fact that the material involved in the slide was able to follow a curved trajectory and to spread downhill over an area wider than the corridor.

The other type of landslide is block slumping. It is illustrated by the block which has been recognized in the offshore continuation of the southern part of Grand-Brûlé.

Thus, the slide that created the Grand-Brûlé depression may have started as block slumping, and evolved to the stage of debris avalanche in the northern two-thirds of the slide. The buttressing effect of the pre-existing part of the submarine plateau would explain why the southern block did not move further.

Although the activity of Piton de la Fournaise has been closely monitored only since the installation of a volcanological observatory in 1980, some of the deformation and seismic data support the idea of a preferential displacement of the eastern part of the central zone under the pressure of the intrusions (Lénat, 1988; Lénat *et al.*, 1989b). The occurence of future large landslides of the east flank is therefore highly probable.

CONCLUSIONS

The survey presented here constitutes a detailed examination of the submarine part of a mostly subaerial active volcano. It provides knowledge of the volcano beyond the shoreline, which is essential for studying the structure and the evolution of the entire edifice, and may be crucial for forecasting the long term behaviour of the volcano (volcanic and volcanotectonic activities).

The main contribution of the survey concerns the two active rift zones and the gravitational instability of the east flank.

The NE and SE rift zones of Piton de la Fournaise are significantly different from the rift zones that have been described for the volcanoes of Hawaii (Fiske and Jackson, 1972; Fornari, 1987; Lonsdale, 1989). Basically they are built by the same process : successive eruptions from linear vents of magma drained from the central area of the volcano. However unlike typical Hawaiian rift zones that from narrow and long ridges, the NE and SE rift zones of Piton de la Fournaise widen downslope. They may be qualified as "sector rift zones".

The magnitude of mass wasting on the east flank appears significantly greater than was inferred from observation of the subaerial part of the volcano. The volume of the slide materiral largely exceeds that of the Grand brûlé depression alone. Much work remains to be done to establish the timing and mechanism of these events. The preliminary interpretation presented here suggests that mass wasting has occurred through debris avalanches and block slumping.

ADDENDUM

A second survey, "Fournaise 2", was conducted to collect complementary data on the same area (high-resolution sonar images, bottom pictures and rocks samples). The data from this latter survey are not yet fully processed and interpreted (Lénat *et al.*, 1989c; Ollier *et al.*, 1989). However some important results have been established. It is now confirmed that one or more debris avalanches actually occured in the Chenal Vincent. On the sonar images, a typical hummocky topography, composed of blocks (some tens of metres broad and high) in a finer matrix, is observed in the lowed par of the Chenal Vincent and in the Râlé-Poussé area. Moreover, virtually all the material of the submarine plateau consists of subaerially erupted, fragmented lavas. Thus the hypotheses set out above concerning mass wasting phenomena have been fully confirmed.

Acknowledgments

The authors thank the crew of R/V *Jean Charcot* (IFREMER). The survey has hads assistance from the scientific staff of the "Hydroamsterdam" and "Rodrigues" projects, headed respectively by P. Beuzard and R. Schlich. We also thank the CNRS (PIRO) for its support.

We are indebted to D.J.D Fornari for his valuable comments which have substancially improved the manuscipt.

REFERENCES

Averous P. (1983). Esquisse géomorphologique des atterages de l'île de la Réunion. Document Terres Australes et Antarctiques Françaises.

Bachèlery P. (1981). Le Piton de la Fournaise (Ile de la Réunion) : étude volcanologique structurale et pétrologique. Thesis, Univ. Clermont II. France.

Bachèlery P., L. Chevallier (1982). Carte volcano-tectonique du Piton de la Fournaise au 1/50000. Document Institut de Physique du Globe de Paris.

Bachèlery P., J. Montaggioni (1983). Morphostructure du flanc oriental du volcan de la Fournaise, Ile de la Réunion (Océan Indien), *C.R. Acad. Sci. Paris*, **297**, série **II**, 81-84.

Bonneville A., J.P. Barriot, R. Bayer (1988). Evidence from geoid data of a hot-spot origin for the southern Mascarene Plateau and Mascarene Islands (Indian ocean). *J. Geophys. Res.*, **93,** B5, 4199-4211.
Chevallier L., P. Bachèlery (1981). Evolution structurale du volcan actif du Piton de la Fournaise, Ile de la Réunion, Océan Indien Occidental. *Bull. Volcanol.*, **44,** 4, 723-741.
Chevallier L., N. Vatin-Pérignon (1982). Volcano-structural evolution of Piton des Neiges, Réunion Island, Indian Ocean. *Bull. Volcanol.*, **45,** 4, 287-298.
Delorme H., P. Bachèlery, P.A. Blum, J.-L. Cheminée, J.-F Delarue, J.-C. Delmond, A. Hirn, J.-C. Lépine, P. Vincent, J. Zlotnicki (1989). March 1986 episodes at Piton de la Fournaise volcano (Réunion Island), *J. Volcanol. Geotherm. Res.*, **36,** 199-208.
Duffield W.A., L. Stieltjes, J. Varet (1982). Huge landslide blocks in the growth of Piton de la Fournaise, La Réunion, and Kilauea Volcano, Hawaii. *J. Volcanol. Geotherm. Res.*, **12,** 147-160.
Duncan R.A. (1981). Hotspots in the southern oceans – An absolute frame of reference for motion of the Gondwana continents. *Tectonophysics*, **74,** 29-42.
Fisher R.L., G.L. Johnson, B.L. Heezen (1967). Mascarene Plateau, Western Indian Ocean. *Geol. Soc. Am. Bull.*, **78,** 1247-1266.
Fiske R.S., E.D. Jackson (1972). Orientation and growth of Hawaiian volcano rifts : the effect of regional structure and gravitational stresses. *Proc. R. Soc.* (London), **329,** 299-326.
Fornari D.J., A. Malahoff, B.G. Heezen (1978). Volcanic structure of the crest of the Puna Ridge, Hawaii : geophysical implications of submarine volcanic terrain. *Geol. Soc. Amer. Bull.*, **89,** 605-616.
Fornari D.J. (1987). The geomorphic and structural development of Hawaiian submarine rift zones. *U.S. Geol. Surv. Prof. Paper*, **1350,** 125-132.
Fornari D.J., M.O. Garcia, R.C. Tyce, D.G. Gallo (1988). Morphology and structure of Loihi seamount based on Seabeam sonar mapping. *J. Geophys. Res.*, **93,** B12, 15227-15238.
Galdéano A., J.-F. Lénat, F.-X. Lalanne (1989). carte aéromagnétique l'île de la Réunion. Document INSU, Institut de Physique du Globe de Paris, Observatoire de Physique du Globe De Clermont-Ferrand.
Gérard A., A. Lesquer, J.C. Lachaud, P. Louis (1980). Etude gravimétrique de la moitié sud-est de l'île de la Réunion. *C. R. Acad. Sc. Paris*, **290,** 139-142.
Gillot P.-Y., P. Nativel (1984). K-Ar chronology of the ultimate activity of Piton des Neiges volcano, Réunion Island, indian Ocean. *J. Volcanol. Geotherm. Res.*, **13,** 131-146.
Gillot P.Y., P. Nativel. Eruptive history of Piton de la Fournaise volcano, Reunion island, Indian Ocean. In press. *J. Volvanol. Geotherm. Res.*, **36,** 33-65.
Kieffer G., B. Tricot, P.M. Vincent (1977). Une éruption inhabituelle (avril 1977) du Piton de la Fournaise (Ile de la Réunion) : ses enseignements volcanologiques et structuraux. *C. R. Acad. Sc. Paris*, **285,** D, 957-960.
Lénat J.-F. (1987). Structure et Dynamique internes d'un volcan basaltique intraplaque océanique : le Piton de la Fournaise (Ile de la Réunion). Thesis, Univ. Clermont II, France.
Lénat J.-F. (1988). Patterns of volcanic activity of Piton de la Fournaise (Réunion Island, Indian Ocean). A synthesis based on monitoring data between 1980 and July 1985, and on historic records since 1930. Proceedings in Volcanology, vol. **1**, Contr. **19,** 312-338. Springler-Verlag Ed.
Lénat J.-F., P. Bachèlery (1988). Dynamics of magma transfers at Piton de la Fournaise volcano (Réunion Island, Indian Ocean). Earth Evol. Sci. Special issue "Modeling of volcanic processes", Chi-Yu and R. Scarpa Eds., Friedr. Vieweg and Sohn, Braunschweig/Wiesbaden, 57-72.
Lénat J.-F., P. Vincent, P. Bachèlery (1989a). The off-shore continuation of an active basaltic volcano : Piton de la Fournaise (Réunion Island, Indian Ocean) : structural and geomorphological interpretation from Seabeam mappin. *J .Volcanol. Geotherm. Res.*, **36,** 1-36.
Lénat J.-F., P. Bachèlery, A. Bonneville, A. Hirn (1989b). The beginning of the 1985-1987 eruptive cycle at Piton de la Fournaise; new insights in the magmatic and volcano-tectonic systems. *J. Volcanol. Geotherm. Res.*, **36,** 209-232.
Lénat J.-F., P. Cochonat, P. Bachèlery, P. Boivin, B. Cornaglia, C. Deniel, Ph. Labazuy, E. Le Drezen, P.W. Lipman, G. Ollier, B. Savoye, P. Vincent, M. Voisset (1989c). Large landslides on the submarine east flak of Piton de la Fournaise volcano : new results from high-resolution sonar imaging and rock sampling. IAVCEI meeting, Santa Fe, 25 June-1 July 1989, abstract published in *New Mexico Bureau of Mines and Mineral Resources Bulletin*, **131, 162.**
Lipman P.W., J.P. Lockwood, R.T. Okamura, D.A. Swanson, K.M. Yamashita (1985). Ground deformation associated with the 1975 magnitude 7.2 earthquake and resulting changes in activity of Kilauea volcano, Hawaii. *U.S. Geol. Surv. Prof. Paper*, **1276.**
Lipman P.W., W.P. Normark, J.G. Moore, B.W. Wilson, C.E. Gutmacher (1988). The giant submarine Alika debris slide, Mauna Loa Hawaii. *J .Geophys. Res.*, **93,** B5, 4279-4299.
Lonsdale P. (1989). A geomorphological reconnaissance of the submarine part of the east rift zone of Kilanea volcano, Hawaii, *Bull. Volcanol.*, **51,** 123-144.
Malahoff A. (1987). Geology of the summit of Loihi seamount submarine volcano. U.S. *Geol. Surv. Prof. paper*, **1350,** 133-144.
Malahoff A., F. McCoy (1967). The geologic structure of the Puna submarine ridge Hawaii. *J. Geophys. Res.*, **72,** 541-548.
McDougall I. (1971). The geochronology and evolution of the young volcanic island of Reunion (Indian Ocean). *Geochem.* Cosmochim. Acta, **35, 3,** 261-288.
Mark R.K., et J. Moore (1987). Slopes of the Hawaiian ridge. *U.S. Geol. Surv. Prof. Paper* **1350,** 101-107.
Montaggioni L. (1978). recherches géologiques sur les complexes récifaux de l'archipel des Mascareignes (Océan Indien Occidental). Thesis, Univ. Aix-Marseille, France.
Moore J.G. (1971). bathymetry and geology-east cape of Hawaii. *U.S. Geol. Surv. Miscellanous geological investigations map*, **I-677,** scale 1/62500.
Moore J.G. (1987). Subsidence of the Hawaiian ridge. *U.S. Geol. Prof. Paper* **1350,** 85-100.
Morgan W.J. (1981). Hot spots tracks and the opening of the Atlantic and Indian oceans. In C. Emiliani Editor, The Sea, 7, the oceanic lithosphere. Wiley, New York, 443-487.
Ollier G., P. Cochonat, J.-F. Lénat, P. Bachèlery, P. Boivin, B. Cornaglia, C. Deniel, Ph. Labazuy, E. Le Drezen, P. Lipman, B. Savoye, P. Vincent, M. Voisset. Sedimentary processes on the submarine flanks of a volcano (Piton de la Fournaise, Réunion Island). Preliminary results of sidescan sonar cruise. 10th regional Meeting of Sedimentology, Budapest (Hungary), April **24-26,** 1989.
Philippot F. (1984). La sédimentation volcanogène récente autour de l'île de la Réunion. Thèse 3[e] cycle. Univ. Paris Sud Orsay, 213 pp.
Puviland P. (1986). Réinterprétation des données géophysiques au vu des résultats des forages SR1 et SLZ1. In Bilan de l'exploration géothermique de l'île de la Réunion. Rapport *BRGM*, **86,** CFG/019.
Rançon J.-Ph., P. Lerebour, T. Augé (1989). The Grand brûlé exploration drilling : new data on the deep framework of the Piton de la Fournaise volcano. Part 1 : Lithostratigraphic units and volcanostructural implications. *J. Volcanol. Geotherm. Res.*, **36,** 113-127.
Rousset D., A. Bonneville, J.F. Lénat (1987). Detailed gravity study of the off-shore structure of Piton de la Fournaise volcano, Reunion Island. *Bull. Volcanol.*, **49,** 813-722.
Rousset D., A. Lesquer, A. Bonneville, J.F. Lénat. Complete gravity study of Piton de la Fournaise volcano, Reunion. *J. Volcanol. Geotherm. Res.*, **36,** 37-52.
Schilch R. (1982). The Indian Ocean : aseismic ridges, spreading centers, and oceanic basins. In *"The Oceans basins and margins"*, vol. **6,** The Indian Ocean. Nairn A.E.M. and Stelhi F.G. editors, Plenum Press, New York, 51-147.
Swanson D.A., W.A. Duffield, R.S. Fiske (1976). Displacement of the south flank of Kilauea volcano : the result of forceful intrusion of magma into rift zones. *U.S. Geol. Surv. Prof. Paper*, **963.**
Vincent P., G. Kieffer (1978). Hypothèse sur la structure et l'évolution du Piton de la Fournaise (Ile de la Réunion) après les éruptions de 1977. *6[e] réun. Ann. Sc. Terre*, Orsay (Soc. Geol. France Edit.), p. 407).