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Three-dimensional structure of the submarine flanks of La Réunion inferred from geophysical data

Lydie-Sarah Gailler¹ and Jean-François Lénat¹

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[1] La Réunion (Indian Ocean) constitutes a huge volcanic oceanic system of which most of the volume is submerged. We present a study of its submarine part based on the interpretation of magnetic and gravity data compiled from old and recent surveys. A model of the submarine internal structure is derived from 3-D and 2-D models using constraints from previous geological and geophysical studies. Two large-scale, previously unknown, buried volcanic construction zones are discovered in continuation of the island's construction. To the east, the Alizés submarine zone is interpreted as the remnants of Les Alizés volcano eastward flank whose center is marked by a large hypovolcanic intrusion complex. To the southwest, the Etang Salé submarine zone is interpreted as an extension of Piton des Neiges, probably fed by a volcanic rift zone over a large extent. They were predominantly built during the Matuyama period and thus probably belong to early volcanism. A correlation exists between their top and seismic horizons recognized in previous studies and interpreted as the base of the volcanic edifice. Their morphology suggested a lithospheric bulging beneath La Réunion, not required to explain our data, since the seismic interfaces match the top of our volcanic constructions. The coastal shelf coincides with a negative Bouguer anomaly belt, often associated with magnetic anomalies, suggesting a shelf built by hyaloclastites. A detailed analysis of the offshore continuation of La Montagne Massif to the north confirms this hypothesis. The gravity analysis confirms that the bathymetric bulges, forming the northern, eastern, southern, and western submarine flanks, are predominantly built by debris avalanche deposits at the surface.

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1. Introduction

[2] Oceanic volcanic islands usually have a long and complex history of volcanic and volcano-tectonic events. This history is always difficult to unravel, both on land, because of the resurfacing by subsequent activity and erosion, and offshore, where geological information is difficult to access. Since the 1980s, a substantial amount of works has been carried out to study the submarine flanks of volcanic islands, especially the Hawaiian Islands [Moore *et al.*, 1989, 1994], Canary Islands [Carracedo, 1999; Krastel *et al.*, 2001; Urgeles *et al.*, 1999] and Réunion Island [Lénat *et al.*, 1990; Oehler *et al.*, 2008; Ollier *et al.*, 1998]. Published studies have usually been limited to the analysis of the submarine flanks surface using bathymetry, imagery and dredging or coring of the shallow rocks. In this work, we present a new approach for studying the 3-D structure of the submarine flanks of La Réunion. In order to extend the investigation at depth, we have analyzed the gravity and magnetic anomalies asso-

ciated with the flanks structures. The distribution of both the density and the magnetization allows us to reconstruct the 3-D geometry of the main geological units, regardless of whether they extend to the surface or have been buried by subsequent products.

[3] New magnetic and gravity data sets have been compiled using the data from old and recent surveys. The interpretation of the magnetic anomalies is effective for distinguishing the constructed structures which retain a coherent remanent magnetization, from the ones formed by breccias (debris avalanches, etc.) which exhibit only a weaker induced magnetization. In addition, because La Réunion volcanism encompasses at least one magnetic reversal (Brunhes-Matuyama), the strong thermoremanent component of the constructed structures gives rise to positive or negative anomalies, depending upon their ages. Interpretation of the gravity anomalies allows the submarine flank materials to be differentiated and characterized due to their density contrast. For example, gravity confirms that huge bulges described by Oehler *et al.* [2008] are mostly built up of low-density material inferred to represent accumulations of debris avalanche deposits.

[4] We have been thus able to reconstruct the morphology of the submarine constructed zones which are concealed by

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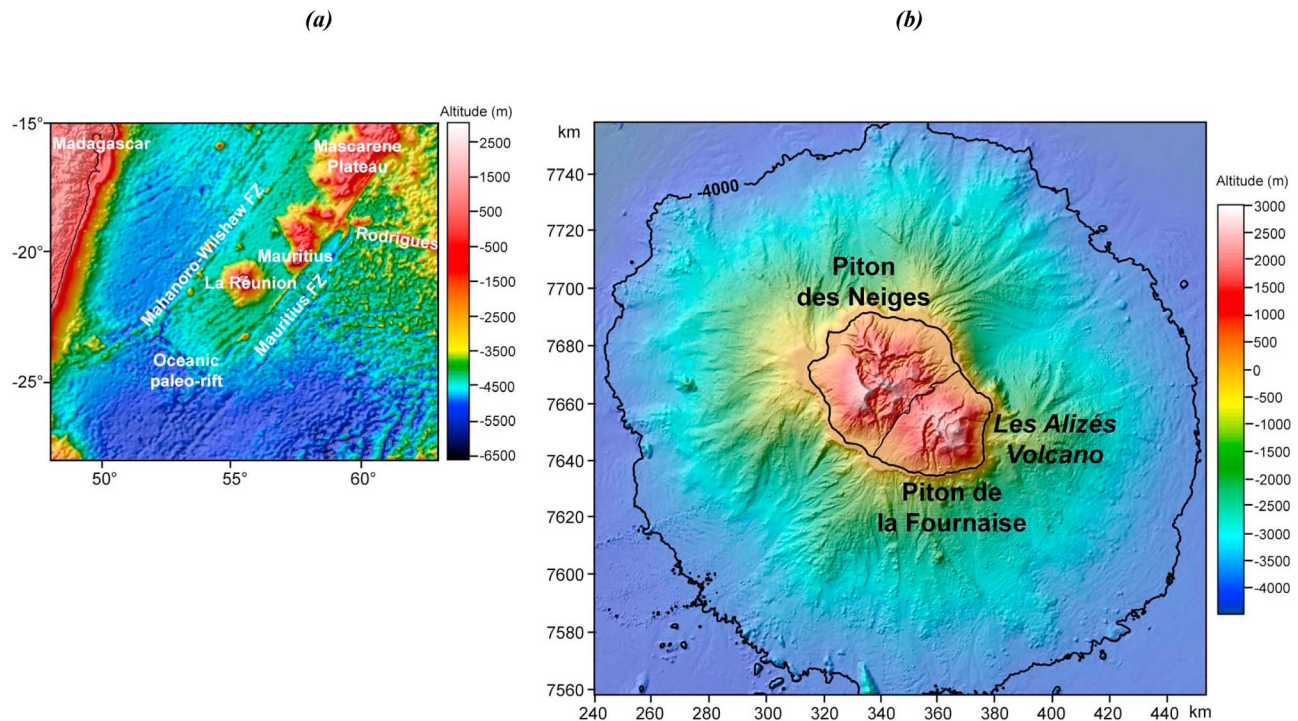


Figure 1. (a) Location of La Réunion in the southwest Indian Ocean. (b) Shaded topography of the island and surrounding seafloor (isobath -4000 m shown), compiled from Institut Géographique National (IGN), Service Hydrographique et Océanographique de la Marine (SHOM), Formation et Evolution de l'Edifice de la Réunion (FOREVER), and Erosion et Démantèlement de l'Edifice volcanique de la Réunion (ERODER) data; Coordinates in km, WGS84 UTM 40S. FZ, fracture zone.

subsequent mass wasting deposits. Unforeseen, very large, extensions of the volcanic constructions of La Réunion have been discovered to the east and southwest of the island. This result is compared with those of previous seismic studies by *de Voogd et al.* [1999] and *Pou Palomé* [1997], and the bulging of the lithosphere proposed by them is challenged by our new model. The nature of the coastal shelf and of the submarine flanks is explored by gravity and magnetic modeling. The coastal shelf appears to correspond mostly to deltas of pillow lavas and hyaloclastites. The four main bulges of the flanks are probably built dominantly by accumulation of debris avalanches deposits, virtually from the seafloor to their surface. In detail, lateral density contrasts within these bulges are tentatively correlated to the distribution of the different geological units observed at the surface.

[5] A general model of the internal structure of the submarine part of La Réunion is proposed, based on our new geophysical 3-D image, together with the results from previous works.

2. Geological Description and Previous Studies

2.1. Geodynamic Context and General Shape

[6] La Réunion, a large intraplate volcanic system in the Mascarene Basin (Indian Ocean, Figure 1a), is widely considered as the expression of a mantle plume [*Duncan et al.*, 1989]. This flattened edifice (Figure 1b), 220 to 240 km in diameter at the level of the surrounding seafloor, reaches about 7 to 8 km in height. It was built on Upper Cretaceous to Paleocene oceanic lithosphere created by a system of

NW-SE paleorift segments separated by NE-SW fracture zones (e.g., Mahanoro-Wilshaw or Mauritius fracture zones, Figure 1a). The island, in a strict sense, is elliptical in shape (50×70 km) with a NW-SE orientation and rises to more than 3000 m above sea level. On this surface, it consists of two juxtaposed volcanic massifs: Piton des Neiges and Piton de La Fournaise volcanoes.

2.2. Island Volcanoes

[7] Piton des Neiges occupies the northwestern part of the island. It is a dormant volcano whose youngest eruptive products are dated at 12 ka [*Deniel et al.*, 1992]. Its subaerial history started with the building of a basaltic shield volcano before 2.08 Ma (age of the oldest outcropping lava flows) to about 0.423 Ma (oceanic series) [*McDougall*, 1971]. Piton des Neiges then erupted alkaline-differentiated lavas between 330 and 12 ka (differentiated series) [*Deniel et al.*, 1992; *Gillot and Nativel*, 1982; *McDougall*, 1971]. Morphologically, this old massif is dissected by deep valleys and three major central depressions locally called cirques.

[8] Piton de La Fournaise occupies the southeastern part of the island. It is a highly active basaltic shield volcano whose recent activity is concentrated on the central cone and along its northeast and southeast rift zones. Piton de La Fournaise has been active from at least 0.527 Ma [*Gillot and Nativel*, 1989]. *Bachèlery and Mairine* [1990] and *Bachèlery and Lénat* [1993] distinguished two phases of building, with the “ancient shield” (>0.15 Ma) and the “recent shield” (<0.15 Ma), comprising several volcano-tectonic events. Some of these events are recognizable on the present morphology as a

series of caldera-like rims and arcuate rims of valleys. These structures could result either from classic caldera collapses [Bachèlery and Mairine, 1990; Bachèlery, 1995] or from successive, eastward moving landslides [Duffield *et al.*, 1982; Labazuy, 1996; Lénat *et al.*, 2001].

[9] The presence of a third, buried volcano has been inferred from gravity [Gailler *et al.*, 2009; Malengreau *et al.*, 1999], magnetic [Lénat *et al.*, 2001] and drill hole [Rançon *et al.*, 1989] data on the eastern coastal area of Piton de la Fournaise. Named Les Alizés, this volcano is known only by its large intrusive and cumulate complex encountered at a depth of 1000 m beneath the Grand-Brûlé area by a geothermal exploration drill hole. This large, extensive and deeply rooted complex has not been associated with any known volcanic structure. It has therefore been regarded as an ancient volcanic center predating Piton de la Fournaise. Negative magnetic anomalies offshore of the eastern coast [Lénat *et al.*, 2001] suggest that rocks belonging to Les Alizés volcano could be present at a shallow depth in this area. Les Alizés activity would predate, or be partially contemporaneous with, that of Piton des Neiges.

2.3. Previous Submarine Studies

2.3.1. Bathymetry and Sonar Images

[10] The bathymetry around La Réunion remained poorly known until 1983 when a low-resolution map, obtained using a monobeam echo sounder, was published [Averous, 1983]. In 1984, a multibeam sonar bathymetric survey was carried out on the eastern flank of La Réunion [Lénat *et al.*, 1989; Lénat *et al.*, 1990]. In 1988, a high-definition sonar image of this area was acquired using deep-tow sonar, SAR [Cochoinat *et al.*, 1990; Labazuy, 1996; Ollier *et al.*, 1998]. In addition, bottom pictures were taken at selected sites, and rock samples were collected by dredging and coring. These data have provided an image of the nature and distribution of the submarine features to the east of the active volcano [Lénat *et al.*, 2009; Ollier *et al.*, 1998]. In particular, they suggested that with the exception of a few features near the coast, the material on the submarine flank was entirely derived from mass wasting and sedimentation phenomena. In addition, detailed bathymetry for a large area of the southern and southwestern submarine flanks of the island was acquired in 1993 using multibeam echo sounder data [Fretzdorff *et al.*, 1998].

[11] More recently, Oehler *et al.* [2008] made a compilation and interpretation of all the high-resolution multibeam bathymetry and acoustic imagery data collected between 1984 and 2003 on La Réunion. The coverage of the flanks, although not complete, was sufficient to provide the basis for an exhaustive study of the submarine domain of La Réunion. This work allowed the authors to draw the first geological map of the submarine flanks of the overall volcanic system. Different types of submarine features have been identified: a coastal shelf, debris avalanches and sedimentary deposits, erosion canyons, volcanic constructions near the coast, and seamounts offshore. Debris avalanche deposits are by far the most extensive and voluminous formations. Their accumulation has built four huge submarine bulges to the east, north, west, and south of the island, forming fans 20–30 km wide at the coastline and 100–150 km wide at their distal ends, 70–80 km offshore. The source land-

slides have recurrently dismantled the Piton des Neiges, Les Alizés, and Piton de La Fournaise volcanoes.

[12] In 2006 and 2008, still unpublished surveys from the cruises FOREVER, ERODER 1 and its second leg ERODER 2 [Dephus *et al.*, 2009; Sisavath *et al.*, 2009] have provided a complete, high-resolution swath bathymetry and sonar imagery and coverage of the submarine flanks and of the surrounding seafloor.

2.3.2. Seismic Studies

[13] Seismic studies were undertaken in the area during a cruise (named Reusis; Figure S1a in the auxiliary material) in 1993 [Charvis *et al.*, 1999; de Voogd *et al.*, 1999; Gallart *et al.*, 1999] and during the above mentioned FOREVER and ERODER cruises.¹ Reusis data suggested that the crust underlying La Réunion shows virtually no downward flexure, and the authors suggested that it could even be bulging upward in some places. On multichannel seismic reflection profiles, de Voogd *et al.* [1999] identified superficial and deep slumps together with debris avalanches to the south and to the east of the island. Some reflectors were interpreted as slide or decollement surfaces, the deepest being the top of the oceanic sediments.

2.3.3. Gravity and Magnetic Studies

[14] Rousset *et al.* [1987] have published an interpretation of gravity data collected during the 1984 survey on the eastern flank of La Réunion. They describe the eastern border of the positive anomaly associated with a cumulate complex interpreted as the central hypovolcanic intrusion system of Les Alizés which is now well constrained both on land and offshore [Gailler *et al.*, 2009] (Figure 4a). They also evidence the overall low-density of the products that form the eastern flank. Lénat *et al.* [2001] constructed a marine magnetic map of the flanks of La Réunion using the data available at that time. They found reverse anomalies near the coast to the east, the southwest and the north of the island, and proposed 2-D models for interpreting these anomalies. They suggested that the eastern reverse anomaly could correspond to the presence of rocks belonging to Les Alizés volcano.

3. Geophysical Data

3.1. Gravity Data

[15] The new data acquired during the FOREVER and ERODER surveys have provided a homogeneous and precise coverage of the submarine flanks. In addition, good quality data from a transit route of the Gallieni cruise carried out in 1995 have also been included in our data set. The on land data have already been described by Gailler *et al.* [2009]. Figure S1b presents the spatial distribution of gravity data used in this work.

[16] The on land gravity data have been reduced using standard procedures, namely tidal variations and instrumental drift. For marine data, the drift correction has been neglected (e.g., 0.01 mGal during ERODER cruise), but an intersection adjustment has been performed at profile crossings, first for each survey, and then between the different surveys (Table 1). The 1967 International Gravity Formula has been used to determine the theoretical gravity at each

¹Auxiliary materials are available in the HTML. doi:10.1029/2009JB007193.

Table 1. Means and Standard Deviations of the Differences at the Crossing Points of the Marine Gravity Profiles

Survey	Mean; Standard Deviation (mGal)		
	Each Survey	ERODER in FOREVER	Gallieni in ERODER and FOREVER
FOREVER	-0.61; 2.77		
ERODER	-0.085; 0.48	0.071; 1.22	
Gallieni	0.89; 2.64		-0.039; 2.55

station location on the Earth's spheroid. The Bouguer slab correction has been computed considering the Earth's curvature [LaFehr, 1991]. Due to the strong topography of the volcanic edifice, terrain effects are significant on La Réunion. A general assumption in determining the optimal density correction is to consider the value minimizing the correlation between the gravity anomaly and the elevation [Nettleton, 1939].

[17] A series of anomaly maps has been computed for different density correction values ranging from 1.6 to $3.2 \times 10^3 \text{ kg m}^{-3}$ (Figure S2a) in order to determine the minimum correlation between gravity and topography at the scale of the overall edifice. We have studied this correlation especially along a large-scale profile crossing the deep valleys of the edifice as shown in Figure S2b. The on land gravity anomalies and the topography appear strongly correlated for density values ranging from 1.6 to $2.4 \times 10^3 \text{ kg m}^{-3}$, and reversely correlated for values exceeding $2.8 \times 10^3 \text{ kg m}^{-3}$. A density value of $2.67 \times 10^3 \text{ kg m}^{-3}$ appears to better minimizes the anomaly topography correlation across the large, deep valleys of the volcanic edifice. For the submarine flanks, the correlation reaches its minimum around $2.2\text{--}2.4 \times 10^3 \text{ kg m}^{-3}$. In order to make the model interpretation more straightforward, however, a homogeneous reduction density of $2.67 \times 10^3 \text{ kg m}^{-3}$ has been applied to the whole map.

[18] The topographic effects have been corrected using Oasis Montaj software from Geosoft. A far zone correction is computed using a coarse regional Digital Elevation Model (DEM), whereas the near zone correction is computed with a more detailed local one. The near zone is a $5 \times 5 \text{ km}$ square centered on the station and the far zone extends to 167 km .

[19] On land, data have been corrected using a 25 m DEM from the Institut Géographique National for the near zone and a 500 m DEM for the far zone. For the offshore data, because the measurements were collected farther from the surface, we have used a 500 m DEM for the near zone and a 1000 m DEM for the regional corrections. The density of seawater was assumed to be $1.027 \times 10^3 \text{ kg m}^{-3}$.

[20] A very low amplitude and high-frequency noise was often noted on the marine gravity data, and was filtered out using a low-pass filter. In a conventional interpolation, short-wavelength, elongated anomalies intersected by several measurement profiles are usually rendered as strings of ellipsoidal beads attracted by the measurement profiles. In our case, this phenomenon was obvious in several areas. In order to minimize these effects, we have used the "trend enforcement algorithm" from Oasis Montaj user-defined trend lines joining highs (or lows) between adjacent profiles (when they unambiguously belong to the same elongated anomaly). Intermediate values between the profiles are line-

arly interpolated along the trend lines and included in the data set to carry out the final interpolation. This process results in smoother maps with better defined anomaly trends.

[21] An obvious, very long wavelength regional trend oriented NE-SW can be interpreted as being produced by deep crustal structures. In order to focus on the local subsurface structures, this regional low frequency has been estimated by a third polynomial surface (Figure S3b) and subtracted from the observed map (Figure S3a). The resulting residual map represents the local Bouguer anomaly (Figure 2) which will be analyzed below.

3.2. Magnetic Data

[22] The marine magnetic (Figure S1c) data set includes the earlier Hydroamsterdam (1984) and Sonne (1999) cruises and the more recent, FOREVER (2006), ERODER (2006) and its second leg ERODER 2 (2007), ones. The constraints provided by these last, more precise, surveys, allow us to define more clearly the different wavelengths of the magnetic anomalies. On land, we have recompiled an aeromagnetic survey flown in 1986 over La Réunion at 3500 m above sea level [Galdéano *et al.*, 1988].

[23] The on land and marine magnetic data have been reduced using standard procedures, including the correction of the distance between the magnetometer and the ship or the aircraft, the intersection adjustment, and the IGRF reduction. As in the case of the marine gravity data an intersection adjustment has been performed at both aeromagnetic and marine magnetic profile crossing points. For the offshore data, this treatment has been first done for each survey, and then between the different surveys (Table 2).

[24] In order to preserve the short-wavelength signals, we have chosen to construct a composite map at sea level for the marine data and another one at 3500 m in elevation for the on land data. An upward continuation of the marine data at 3500 m would result in a detrimental loss of useful short-wavelength information. On the other hand, because the elevation of the highest summits on land exceeds 3000 m , it is not possible to make a downward continuation of the aeromagnetic data.

[25] We present maps of reduced-to-the-pole (RTP) anomalies, since this transformation reduces significantly the dipolar appearance of the anomalies and offsets them to their sources [Baranov, 1957]. The magnetic maps prior to the RTP transformation, both on land and offshore are presented in the auxiliary material (Figure S4). The direction of the apparent magnetization and that of the ambient field are required to compute a RTP map. The apparent (or total) magnetization corresponds to the sum of the remanent and induced magnetizations. The induced magnetization vector is collinear with the ambient field (present magnetic field vector in La Réunion: declination $\sim 19^\circ$; inclination $\sim 54^\circ$), whereas the remanent magnetization is the combination of various types of magnetizations. For basaltic rocks, the thermoremanent component (TRM) is generally the dominant one. Although the present magnetic field differs significantly from that of a geocentric axial dipole field for that latitude (declination of 0° and inclination of -36°), we have used this direction for the magnetization, since it well represents the TRM direction of the terrains when secular variation effects are averaged, and because the generally high Koenigsberger ratio (i.e., the

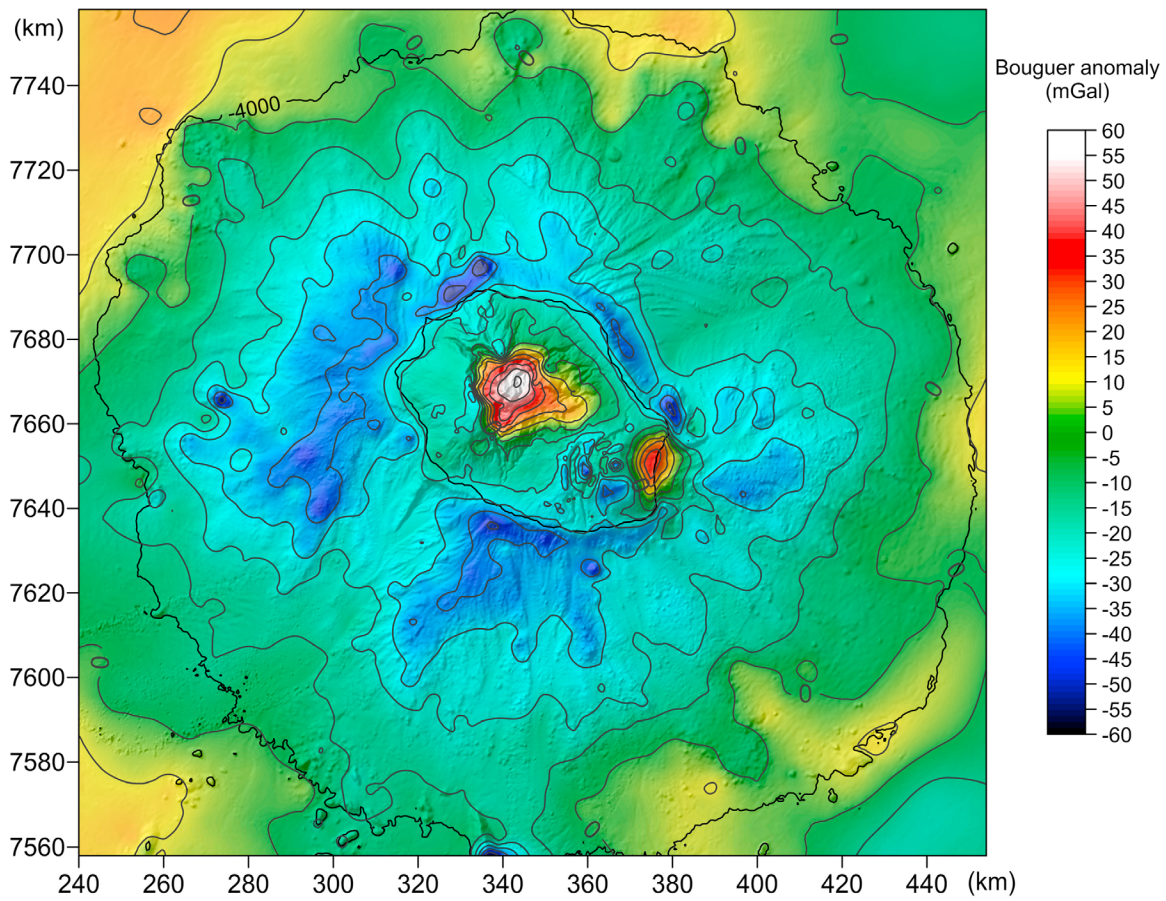


Figure 2. Residual Bouguer anomaly map of the whole edifice of La Réunion (contour interval of 10 mGal). The black solid contours refer to the 0 m and -4000 m isobaths. Coordinates in kilometers (WGS84, UTM 40S).

ratio of the natural remanent magnetization to the induced magnetization) of volcanic rocks indicates a preponderance of the thermoremanent magnetization component over the induced one.

[26] On the submarine flanks and the surrounding sea-floor, we observe moderate to long-wavelength linear anomalies typical of the magnetic fabric of the oceanic crustal structures. We also note the presence of shorter-wavelength and less extensive anomalies located mostly on the upper submarine flanks. These latter volcanic anomalies will be the target of our study. We have therefore filtered the marine

map to minimize the signals related to the oceanic crust (Figure S4). The residual map is shown on Figure 3a.

[27] In order to emphasize the shallow anomalies caused by the volcanic constructions related to La Réunion volcanism, we have calculated the vertical gradient of the RTP map. This magnetic derivative enhances the short-wavelength component of the field and helps to resolve closely spaced or superimposed anomalies. The vertical gradient anomalies are more focused on their causative bodies and can be used to localize the extent of their sources.

Table 2. Means and Standard Deviations of the Differences at the Crossing Points of the Aeromagnetic and Marine Magnetic Profile

Survey	Mean; Standard Deviation (nT)				
	Each Survey	ERODER in FOREVER	Sonne in ERODER and FOREVER	Hydroamsterdam in Sonne, ERODER, and FOREVER	ERODER 2 in Hydroamsterdam, Sonne, ERODER, and FOREVER
Aeromagnetic	7.53; 31.53				
FOREVER	-3.46; 32.65				
ERODER	-5.04; 9.69	0.092; 8.34			
Sonne	-10.85; 13.54		-421.49; 29.7		
Hydroamsterdam	-22.71; 30.87			-1055.23; 56.457	
ERODER 2	-1.85; 11.65				27.52; 36.301

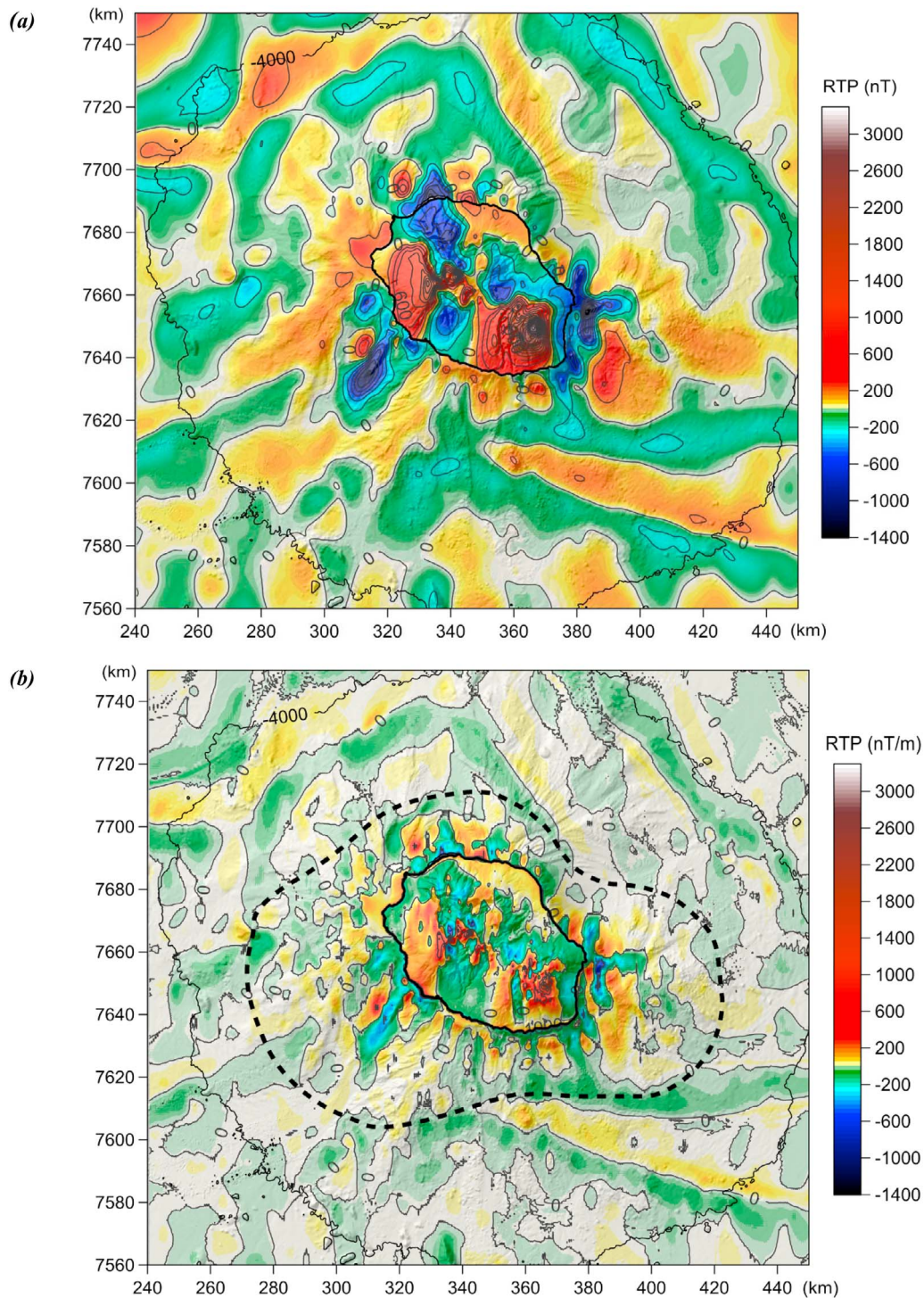


Figure 3. (a) Composite RTP magnetic anomaly map (contour interval of 200 nT): the marine part is computed at sea level and the on-land part is computed at 3500 m. (b) Vertical gradient (contour interval of 500 nT m^{-1}) of the residual RTP map presented in Figure 3a. The black solid contours refer to the 0 m and -4000 m isobaths, and the dashed contour evidences the area dominated by short- to medium-wavelength magnetic anomalies. Coordinates in kilometers (WGS84, UTM 40S).

3.3. Modeling of the Geophysical Anomalies

[28] We have carried out different modeling approaches in order to define the magnetic and gravity structure of the areas of interest. Three-dimensional inversions, computed

using GRAV3D and MAG3D software developed by *Li and Oldenburg* [1998], have allowed us to obtain smooth general models of the magnetization and density distribution, whereas 2-D modeling has been used to derive more detailed

Table 3. Parameters Involved in the Inverse Magnetic Modeling for Each Study Area

Modeled Area	Cell Size $x \times y \times z$ (m)	Number of Cells
Les Alizés area	$200 \times 200 \times 100$	5,116,640
Etang Salé Ridge area	$1000 \times 1000 \times 500$	189,720
La Montagne Massif area	$200 \times 200 \times 100$	5,214,825

models constructed with more geological and geophysical constraints than the 3-D inversions.

3.3.1. The 3-D Inversion

[29] The inversions are carried out on residual magnetic RTP data and residual Bouguer data. The model region is divided up by means of a mesh model with variable eastward and northward extents depending on the area of interest. The size of the finite elements defining the models decreases toward the inner zone, where a higher resolution is required. The range of density and susceptibility, which can be negative to account for a reverse magnetization contrast, is fixed in each cell. In this study, the starting models have homogeneous magnetization or density (0 A m^{-1} and 0 kg m^{-3}), and no magnetization or density bounds have been imposed in the inversion. The parameters of the meshes are given for each study area in the Table 3.

[30] The inversion process tends to account for the observed anomalies with a succession of juxtaposed shallow bodies, with both normal and reverse magnetization, and both positive and negative density values. Some of these bodies are strictly superficial and some extend at depth to the base of the model volume. The different wavelengths of the observed anomalies are thus well reproduced. As is usual with this type of inversion, the structures present very smooth boundaries. As a consequence, we have used this first general approach to construct more detailed 2-D models with sharp boundaries.

3.3.2. The 2-D Models

[31] Since the geometrical constraints are more easily managed in 2-D, 2½-D, and 2¾-D models have been constructed (using GMSYS software). In the 2½-D case, the structures are truncated at the same distance from the section plane in the strike direction, and in 2¾-D the structures are truncated at different distances. In addition, this kind of modeling also permits a strike different from 90° .

3.3.3. General Geological and Geophysical Constraints

[32] Very few constraints exist to infer the geometry of the internal structure of the submarine flanks. Apart from the bathymetry, only the seismic reflection works by *de Voogd et al.* [1999] and *Pou Palomé* [1997] carried out at the east and to the south/southwest of the island provide any information. The authors identify a V reflector as the base of the volcanic construction, above the oceanic sediments, and a shallower one, H, as the top of Les Alizés volcano. However, the authors themselves acknowledge that the interpretation of V is not well established.

[33] The extent of the volcanic system can be assessed with the bathymetry and the seismic data from *de Voogd et al.* [1999]. In the bathymetry, the base of the cone corresponds to a water depth of about $-4000/-4250$ m. In the seismic data an unconformity between the volcanic products and subhorizontal sediments is observed at similar depths. We have therefore assumed that the base of the volcanic cone

lies around -4000 m. It should be stressed that this parameter is not crucial in the construction of the models, because the gravity and magnetic modeling is not usually very sensitive when studying the base of the sources.

[34] With respect to the density and magnetization values used within the models, we have relied on data from the literature concerning La Réunion or similar contexts. Few data exist on the magnetization of La Réunion rocks except three paleomagnetic studies [*Chamalaun*, 1968; *Chauvin et al.*, 1991; *Rais et al.*, 1996], which provides natural remanent magnetization (NRM) and susceptibility values for some particular geological sections in the Piton de la Fournaise and Piton des Neiges volcanoes. As is common for basaltic rocks, the major factor is the thermoremanent magnetization (TRM), and the Koenigsberger ratio (i.e., the ratio of the natural remanent magnetization to the induced magnetization) is high. However, most of the offshore volcanic constructions have probably been emplaced underwater and should be predominantly composed of pillow lavas. Some studies [*Delius et al.*, 2003] show a lower remanent magnetization for submarine basalts as compared to their subaerial counterparts. Since the magnetization of the underwater formations cannot be precisely constrained in the case of La Réunion, we have kept a realistic range of magnetization of $\pm 8 \text{ A m}^{-1}$ in the models [*Chamalaun*, 1968; *Chauvin et al.*, 1991; *Rais et al.*, 1996].

[35] Density values in the models have been constrained using geophysical and geological observations. The homogeneous reduction density of $2.67 \times 10^3 \text{ kg m}^{-3}$ used to construct the map corresponds to an average density of the whole volcanic system. From measurements on drill hole samples, *Demange et al.* [1989] report densities between 2.5 and $2.9 \times 10^3 \text{ kg m}^{-3}$ for pyroclastites and lava flows, and between 3.1 and $3.35 \times 10^3 \text{ kg m}^{-3}$ for intrusive rocks. In addition, lower density values have been inferred for formations on land and offshore in the interpretation of gravity anomalies [*Gailler et al.*, 2009]. Accordingly, the different types of formations have been modeled using density ranging from 1.6 to $3.2 \times 10^3 \text{ kg m}^{-3}$.

4. Offshore Continuation of the Volcanic Constructions of La Réunion

[36] Three areas, to the east, southwest and north of the island, show volcanic constructions extending from the coast up to some tens of kilometers offshore. Since these constructions are buried beneath the debris avalanche deposits and the sediments covering the submarine flanks, their identification relies mostly on the pattern of the magnetic anomalies.

4.1. Magnetic Signal of Buried Volcanic Constructions on the Submarine Flanks

[37] The RTP maps (Figure 3a) clearly show the presence of both normal and reverse magnetic anomalies extending from the coast up to a few tens of kilometers offshore. These anomalies do not coincide with the extent and the shape of the submarine flanks. The vertical gradient map allows us to differentiate clearly these anomalies associated with the volcanic constructions from those of the crust due to their shorter wavelengths, which indicate a shallower origin. We can therefore infer that these anomalies are generated by volcanic constructions related to La Réunion volcanism. Another

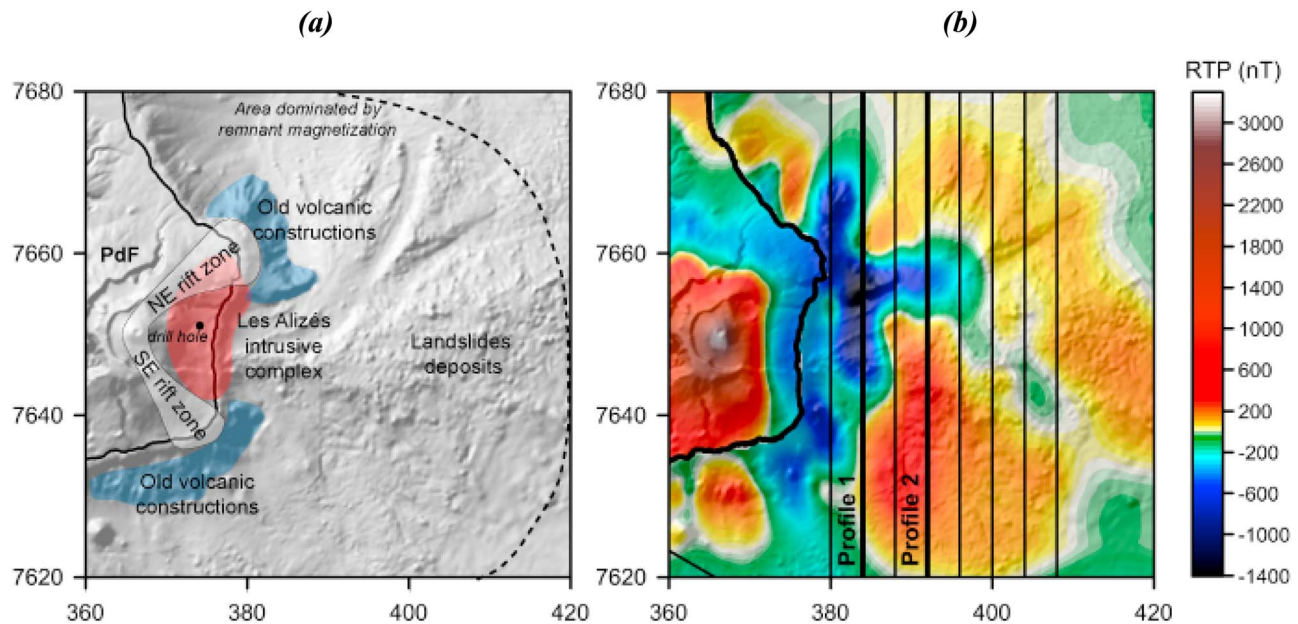


Figure 4. (a) Map showing the major features associated with the eastern part of La Réunion: the Piton de la Fournaise (PdF) rift zones, the inferred old volcanic constructions in their continuation [Lénat *et al.*, 1989, 1990], the drill hole location in the Grand Brûlé area, Les Alizés intrusive complex evidenced by the drill hole and the gravity data, and the landslide deposits characterized by a chaotic topography. Les Alizés intrusive complex extension is derived from the -1400 m contours of our 3-D model presented in Figure 5. (b) Extract of the composite RTP magnetic anomalies map (Figure 3a) centered on the eastern area of La Réunion, with the location of the profiles studied in Figure 4c. (c) The $2\frac{3}{4}$ -D models of the magnetic anomalies along the profiles located in Figure 4b in thicker lines. The bottom sections show the $2\frac{3}{4}$ -D magnetic models in the foreground, superimposed on the corresponding sections in the 3-D inversion model in the background. The 2-D structures are truncated at a distance of 26 km eastward and 19 km westward from the profile direction in Figure 4a and at a distance of 18 km eastward and 27 km in Figure 4b. The normally and reversely magnetized structures are represented in red and in blue, respectively. Coordinates in kilometers (WGS84, UTM 40S).

independent argument is the relatively high amplitude of the anomalies, comparable to the on land ones. As previously shown, mafic volcanic rocks, such as those from La Réunion, generally have a very high magnetization and their total magnetization is dominated by the thermoremanent component. The high proportion of reverse anomalies indicates that the sources have kept a coherent thermoremanent component of magnetization and, consequently, that a large portion of these volcanic constructions predates the Bruhnes-Matuyama reversal. By contrast, the rest of the submarine flanks, which are thought to be mostly constructed of accumulated breccias and sediments [Oehler *et al.*, 2008], are virtually “transparent” from a magnetic point of view. Within breccias, the thermoremanent components of the blocks are randomly oriented, leaving only a relatively weak induced magnetization component. Therefore, the breccias do not generate magnetic anomalies comparable in amplitude to that of massive volcanic constructions.

4.2. Extent of the Magnetic Anomalies Associated With Volcanic Constructions

[38] The vertical gradient map (Figure 3b) enables the signal of the shallowest sources to be amplified. Therefore, the short-wavelength anomalies of the vertical gradient correspond to the geometric and magnetization heterogeneities in

the shallow parts of the sources bodies of the RTP anomalies shown in Figure 3a. Accordingly, the distribution of this short-wavelength signal can be used to map the extent of the volcanic constructions around La Réunion, which form a continuous belt around the island as underlined on Figure 3b. To the east and southwest the belt is shown to be significantly larger than in the other sectors.

4.3. Eastern Submarine Anomalies

4.3.1. Geological Setting

[39] The eastern zone of La Réunion (Figure 4a) has long been recognized as a particular area within the volcanic system, being both the site of the presently active volcanic part of the island and the location of the old Les Alizés volcano [Lénat *et al.*, 2001]. Offshore, the area is covered by sediments and landslides products. Most of the landslide breccias on the surface have a subaerial origin and are younger than 115 ka [Cochonat *et al.*, 1990; Labazuy, 1996; Lénat *et al.*, 1989; Lénat *et al.*, 2009; Oehler *et al.*, 2008; Ollier *et al.*, 1998]. However, an age of 2.8 Ma was measured on a dredged sample [Lénat *et al.*, 2009], suggesting that parts of Les Alizés volcano could be involved in the mass wasting events of this area, as also suggested by Oehler *et al.* [2008]. In addition, offshore reliefs approximately along the NE and SE continuation of the Piton de la

(c)

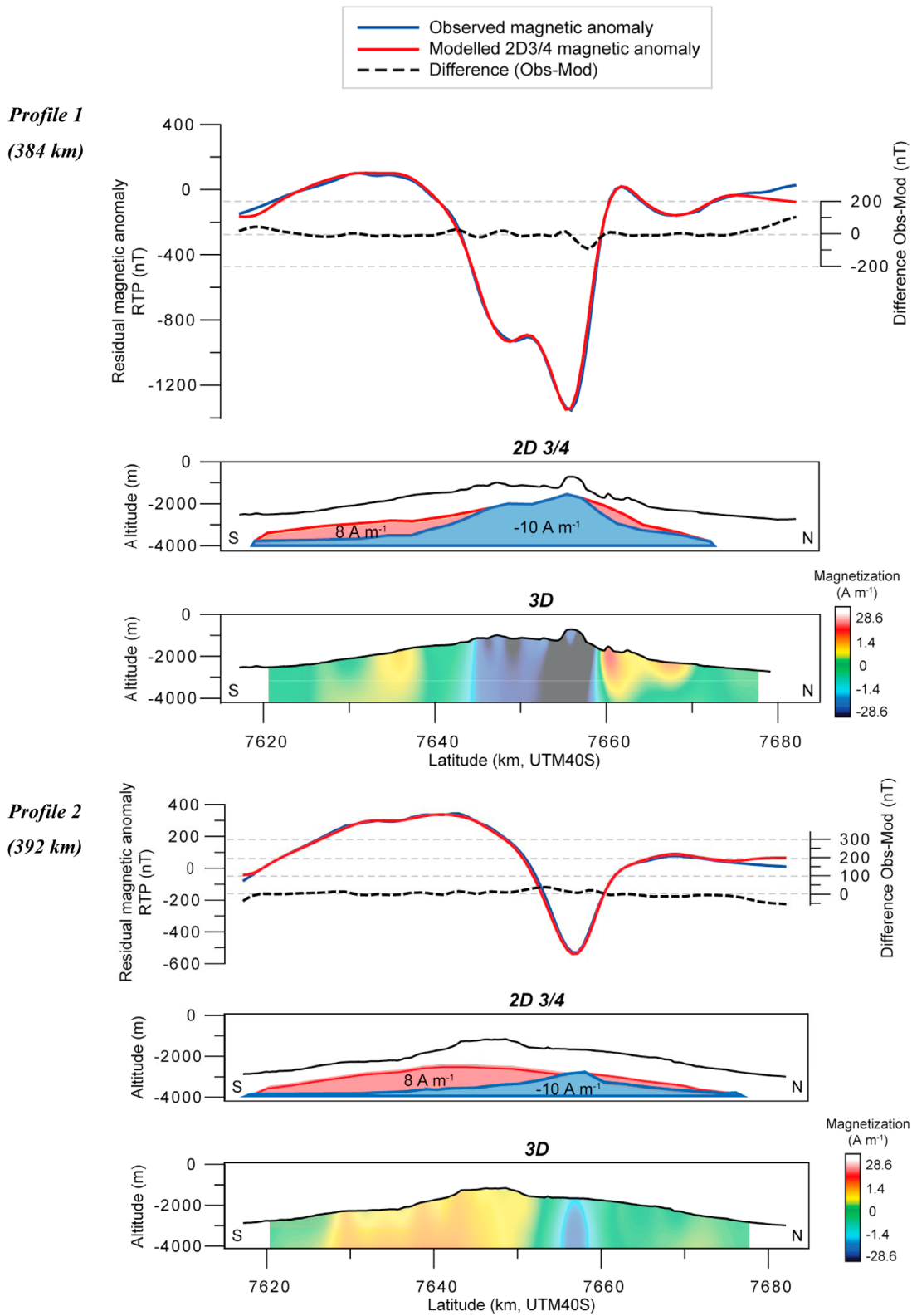


Figure 4. (continued)

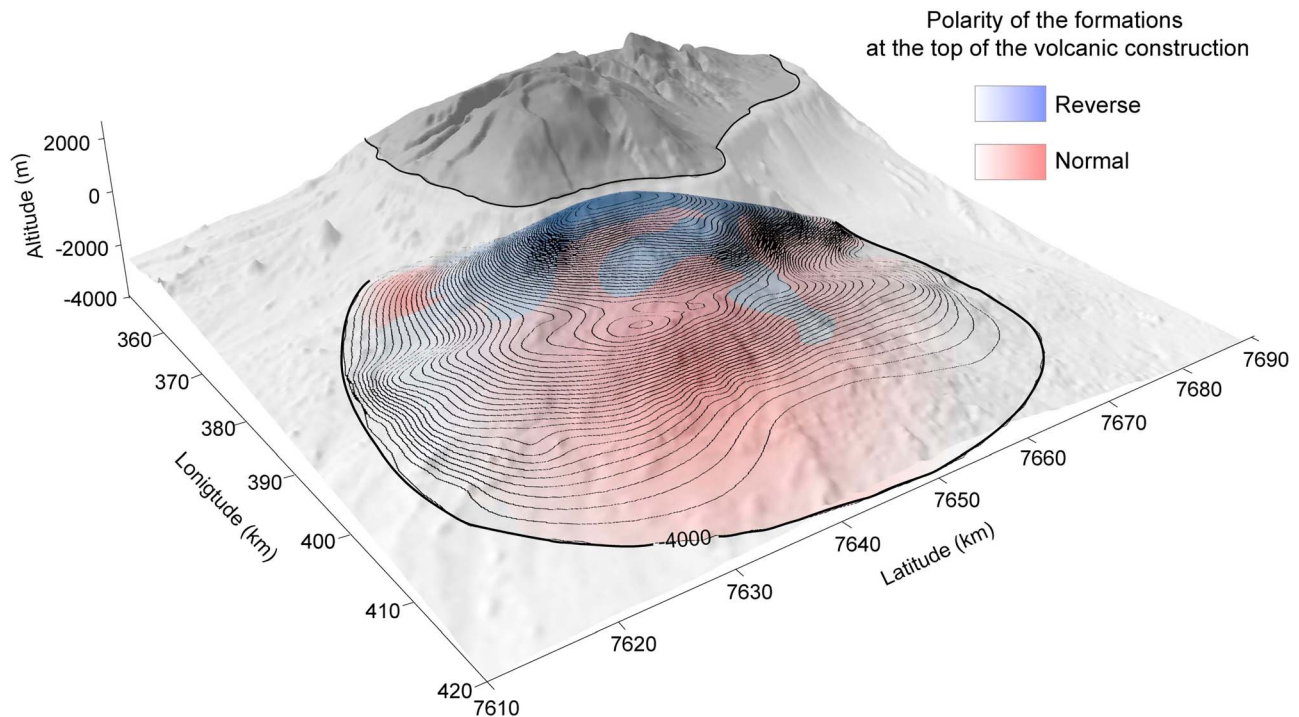


Figure 5. The 3-D morphology of the eastward submarine flank of Les Alizés volcano surface reconstructed using the results of the 2^{3/4}-D modeling. The contours represent the top of the magnetic structures obtained through modeling (contours interval of 50 m).

Fournaise rift zones have been regarded as remnants of volcanic constructions predating the Piton de la Fournaise [Lénat *et al.*, 1989; Lénat *et al.*, 1990].

4.3.2. Description and Modeling of the Magnetic Anomalies

[40] The eastern area is characterized by high amplitude, mostly negative anomalies (Figure 4b). In addition, near the coast, the negative anomalies appear along the continuation of on land negative anomalies in association with recent lava flows from the Piton de la Fournaise which may appear as conflicting. However, Gailler and Lénat [2010] show that the Piton de la Fournaise lava pile is rather thin in this area and underlain by reversely magnetized formations. The presence of both negative and positive anomalies offshore indicates unambiguously that the anomalies are created by layers which have preserved their original geological coherence, and that the signal is dominated by their thermoremanent component of magnetization. Moreover, the negative anomalies indicate that part of the source is older than the Brunhes-Matuyama magnetic reversal (0.78 Ma).

[41] The short- to medium-wavelengths character of the anomalies suggest a rather shallow depth to the top of the sources, as also indicated by the strong vertical gradient in this area (Figure 3b). A correlation is observed near the coast between the location of the negative anomalies and the relief interpreted as old volcanic constructions predating the present rift zones of Piton de la Fournaise (Figure 4b). Elsewhere, the anomalies do not coincide with any known surface structures, suggesting that a large part of the volcanic construction lies buried in this zone. The modeling of the anomalies will help us to determine the location and the morphology of these constructions.

[42] A 3-D inversion has been carried out and 2^{3/4}-D models have been constructed along 7 evenly spaced profiles oriented north to south between the coast and the eastern tip of the anomalies (Figure 4c). The base of the structures is fixed at -4000 m according to the assumption described above, and both the shape and the magnetization are adjusted to account for the observed anomalies.

[43] Since any magnetic (or gravity) anomaly can be accounted for by an infinite number of different sources, the modeling of magnetic and gravity anomalies presents a problem known as the “nonuniqueness problem.” However, the domain of the solutions is drastically limited when geologically plausible constraints, such as geometry, magnetization and density values, are specified in the models. In this work, the 2^{3/4}-D models are constructed to obtain the simplest possible source shapes, while their geometry and magnetization remain compatible with the geological observations. Since the modeling suggests that both normal and reversely magnetized bodies are present, we have assumed that the reversely magnetized formations are located beneath the normally magnetized ones, when these latter are present. We therefore propose that anomalies are caused only by normally magnetized Brunhes and reversely magnetized Matuyama constructions. Figure 4c shows two sections illustrating the 3-D and 2^{3/4}-D modeling results along the two profiles located in Figure 4b. The other 2^{3/4}-D models used in the 3-D reconstruction are presented in the auxiliary material (Figure S5a).

[44] Figure 5 is a 3-D rendering of the inferred model surface, built by interpolation of the 2-D models along the seven profiles presented in Figure S5a. It shows the general morphology of the offshore construction. The general shape

of this concealed portion of La Réunion volcanism is that of a volcano flank, becoming thinner offshore and connecting to the on land construction. In addition, the lateral extent of this structure is compatible with that of a flank of Les Alizés volcano lying around the Grand Brûlé hypovolcanic complex.

4.4. Comparisons With the Seismic Data and Interpretations

[45] On the offshore seismic reflection profiles from the Reusis survey, the two main interfaces identified by *de Voogd et al.* [1999] and *Pou Palomé* [1997] (the top of the oceanic basement (B) and the top of the sediments, named the base of the volcanoclastic edifice (V) by the authors) are separated, on average, by 600 m of oceanic sediments. A third interface H, has been observed on some profiles between V and the surface.

[46] Identifying V as the base of the volcanoclastic edifice, *de Voogd et al.* [1999] and *Pou Palomé* [1997] propose that the crust is bulging upward in this area (see Figure 8 in section 4.5). The H horizon follows the same pattern and *Pou Palomé* [1997] suggests that it could also represent the top of Les Alizés volcano.

[47] Considering the relative accuracy of the two methods, a striking convergence is observed between the topography of the crust bulge inferred by the authors of the seismic interpretation and that of the volcanic construction derived from our magnetic interpretation (Figure 8). Thus the question of the nature of this apparent bulge must be resolved in order to understand the evolution of this area.

[48] The magnetic signature of this area seems incompatible with that of a bulged oceanic lithosphere. The oceanic crust is typically characterized by long-wavelength positive and negative strips. Although the pattern of oceanic magnetic anomalies is quite complex around La Réunion [*Bissessur et al.*, 2009], the latter are easily differentiated from the short-wavelength and heterogeneously distributed anomalies related to the volcanic construction (Figure 3a). An upwardly flexed oceanic lithosphere could not create the short-wavelength alternation of positive and negative anomalies observed over the eastern offshore zone of La Réunion (Figures 3 and 4). Accordingly, we infer that the V and H seismic horizons do not correspond to a bulge of the lithosphere in this area, but to the top, or internal interfaces of a buried, still coherent, part of the volcanic construction of La Réunion. The shape and lateral extent of this construction is fully compatible with the remnants of the eastern flank of Les Alizés volcano which is now almost completely buried beneath subsequent products resulting from constructive and destructive processes of the volcanic edifice.

[49] This interpretation can be generalized to the northern and southern parts of the island in the areas covered by the *de Voogd et al.* [1999] survey. In this, the authors also propose that the oceanic crust is rising upward toward the island (Figure 8). However, this apparent bulging has a much lower offshore extent than that of the eastern area. From a magnetic point of view, the areas where *de Voogd et al.* [1999] propose a crustal bulge correspond to the belt of short-wavelength magnetic anomalies with normal and reverse polarity. On the basis of the modeling carried out for the eastern anomalies, we infer that this part of anomaly belt, to the east and to the southwest also corresponds to

volcanic constructions unrelated to the oceanic plate. In the other places around the island apart to the north, as we will see hereafter, the volcanic constructions do not extend very far offshore, and the anomaly belt would thus just be generated by rocks from the natural slope of the volcanic construction of the island.

4.5. Southwestern Submarines Anomalies

4.5.1. Geological Setting

[50] The southwestern submarine flank of La Réunion is characterized by the presence of a conspicuous sharp ridge oriented 30°N, about 17 km long, 2–3 km wide and 400–800 m high (Figure 6a). This ridge, named Etang Salé Ridge (ESR), is located at the saddle between the southern and eastern bulges of the submarine flanks [*Oehler et al.*, 2008]. *Lénat et al.* [2001] have suggested that it could be an ancient rift zone of the Piton des Neiges which has been partially eroded by mass wasting events. The on land continuation of the ridge is characterized by an alignment of Strombolian satellite cones observed between the coast and the summit of this flank of the Piton des Neiges volcano (Figure 6a). The cones and their basement belong to the differentiated series (330–12 ka [*Billard and Vincent*, 1974; *Deniel et al.*, 1992; *Deniel*, 1990; *Gillot and Nativel*, 1982; *McDougall*, 1971]) of the Piton des Neiges.

4.5.2. Description and Modeling of the Magnetic Anomalies

[51] As shown on Figures 3 and 6b, this submarine area is characterized by large and extensive magnetic anomalies, comparable to those observed on the eastern submarine flank. The anomalous zone is not restricted to the submarine Etang Salé Ridge, but extends farther offshore (about 38 km) and is wider (about 36 km near the seashore). The area of short- to medium-wavelength anomalies can even be extended if the vertical gradient is considered (Figure 3b), because a high-frequency signal is still present on the lower slopes and the foot of the anomalies. Both positive and negative anomalies are observed, although the latter cover a larger surface. At the shoreline, the magnetic anomaly switches abruptly to being positive. This on land positive anomaly originates from the fact that the volcano flank is covered by a thick sequence of products from the differentiated series (330–12 ka) producing a large positive anomaly [*Lénat et al.*, 2001]. Using the same rationale as for the eastern zone, we infer that the magnetic anomalies in the near offshore zone are caused by the presence of buried volcanic constructions, some of them being older than the Brunhes-Matuyama reversal of 0.78 Ma.

[52] As in the case of the eastern continuation of Piton de la Fournaise, we consider that both negative and positive anomalies are superimposed and could correspond to successive construction stages at different epochs. Along the southwestern submarine ridge, 2³/₄-D models have been constructed along 14 NW-SE evenly spaced profiles between the coast and the southwestern tip of the anomalies (Figure 6b). We found that three significantly different types of models can each explain the observed magnetic anomaly pattern.

[53] In the first type, the positive and negative anomalies can be explained by juxtaposed structures with normal and reverse magnetization as suggested by the 3-D inversion results. The second type is derived from volcanological considerations and is comparable to the models for the eastern

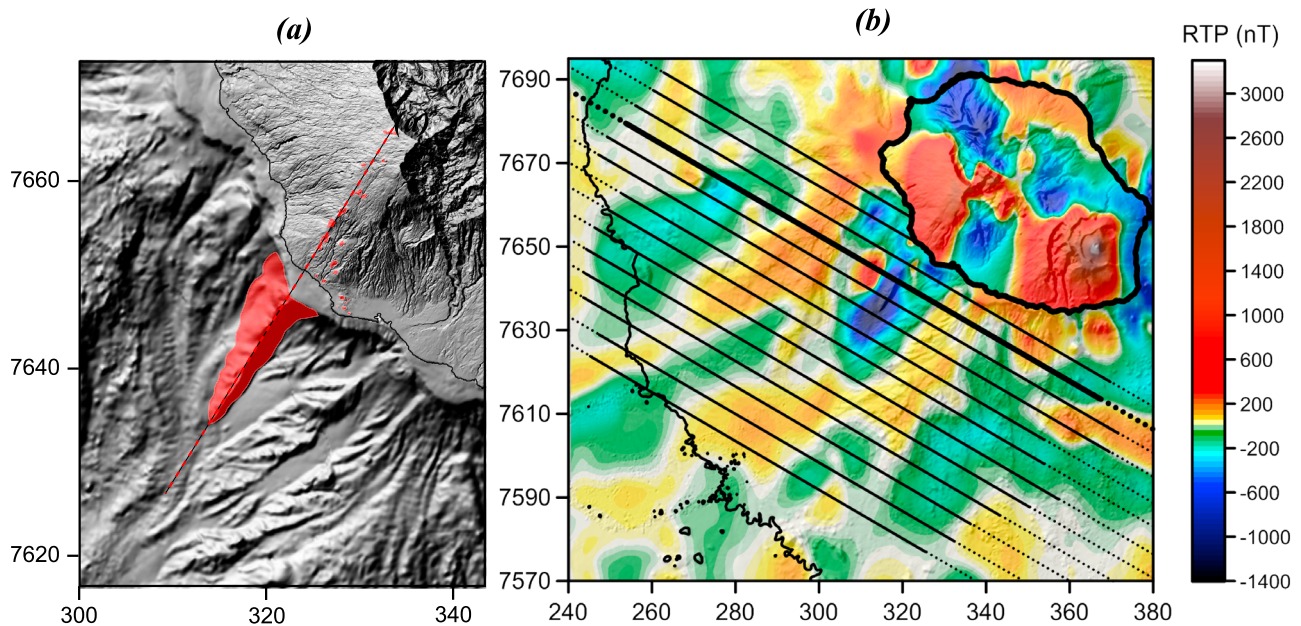


Figure 6. (a) Offshore Etang Salé Ridge (red area) and line of Strombolian parasitic cones (red points) on the southwestern flank of Piton des Neiges, both oriented N30°. Coordinates in kilometers (WGS84, UTM 40S). (b) Southwestern extract of the RTP magnetic anomaly map presented in Figure 3a and location of the profile studied in Figure 6c. (c) The 2^{3/4}-D models of the magnetic anomalies along the profile located in Figure 6a in thicker line. The 2-D structures are truncated at a distance of 25 km northward and 38 km southward from the profile direction in Figure 6a and at a distance of 33 km northward and 30 km southward in Figure 6b. The normally and reversely magnetized structures are represented in red and in blue, respectively. (d) Gravity 2^{3/4}-D model along the same profile. (e) Combination of both magnetic and gravity models. The volcanic constructions defined by the magnetic interpretation (Figure 6b) are modeled with a density of $2.67 \times 10^3 \text{ kg m}^{-3}$, whereas the inferred pile of mass-wasting derived breccias has densities between 1.8 and $2.4 \times 10^3 \text{ kg m}^{-3}$. (f) Slice within the 3-D inversion of magnetic data following the same profile. Coordinates in kilometers (WGS84, UTM 40S).

flank, considering a basal, homogeneous, reversely magnetized structure covered in some areas by normally magnetized formations. In this case, the bathymetric ridge is not considered as a magnetic source. The last set of models is based on the same configuration as the second type, but the magnetized structure includes the bathymetric ridge, that is the upper surface of the modeled construction mimics the topography of this relief. Each type of model satisfies the observed magnetic signal and it is therefore not possible to select one type on modeling arguments alone. From a volcanological point of view, however, we favor the third type of models since it seems more rational to consider that a pile of constructions built during the Matuyama period is covered by constructions built during the Brunhes epoch, where the well defined bathymetric ridge also corresponds to a volcanic constructional feature. The magnetic signal also suggests a stronger magnetization for the ridge and its continuation.

[54] Figure 6c shows a selected section to illustrate the 3-D and 2^{3/4}-D modeling results along the profile located on Figure 6b. The other 2^{3/4}-D models used in the 3-D reconstruction are presented in the auxiliary material (Figure S5b). The upper surface of the overall magnetic structure can be modeled as being relatively smooth, with the surface of the underlying reversely magnetized structure being more chaotic. Within this latter structure, the area corresponding to

the large negative anomaly elongated along a N30° direction is modeled by formations with a higher magnetization. At the northeast, this highly magnetized structure coincides with the Etang Salé Ridge. Downslope, when this bathymetric feature vanishes beneath the volcano-detritic products, the modeled linear structure continues for a further 10 km. However, because of the non-unicity of the solution reliable to the modeling approach, the models cannot resolve the magnetization intensity and polarity of the ridge itself. In Figure 6c, we show that the top of the structure could be normally magnetized.

4.5.3. Joint Interpretation of the Gravity and Magnetic Data

[55] One of the major features of the newly compiled Bouguer anomaly map is the presence of a negative gravity belt at the land-sea transition, together with strong negative anomalies associated with the submarine flanks. However, over the southwestern area where the magnetic anomalies are observed, the gravity signal appears less negative compared to the adjacent southern and western topographic bulges (Figure 2). In order to investigate the gravity signal, several models have been built at different scales.

[56] A 3-D inversion has been carried out on a zone covering the area shown in Figure 6. The result suggests that the anomaly pattern can be primarily explained by consid-

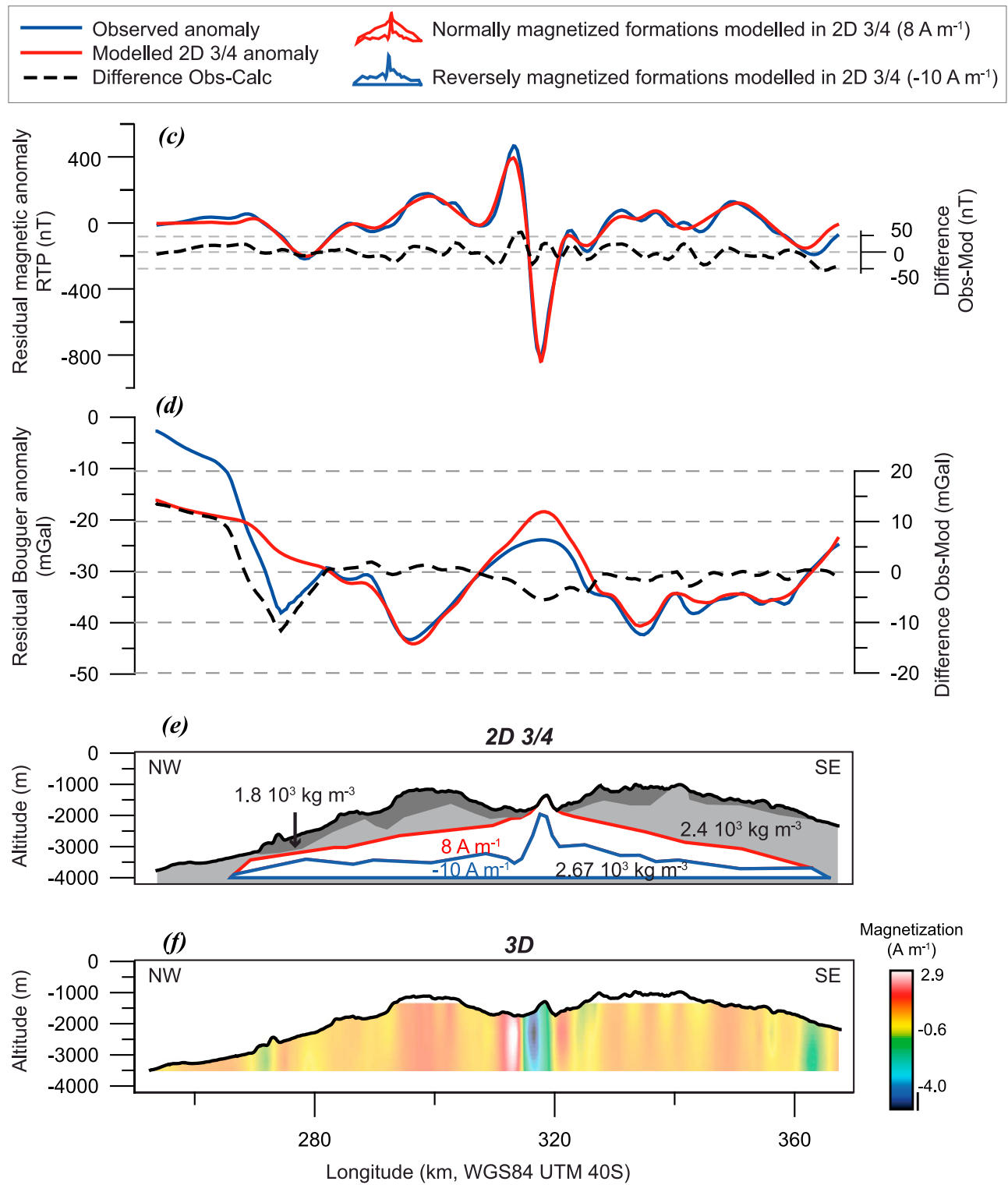


Figure 6. (continued)

ering a relatively lower density for the two large bulges on the NW and SE side of the inferred volcanic ridge.

[57] We have, therefore, explored models explaining both the gravity and magnetic signals. Figure 6d presents the results obtained along profile 1 located in Figure 6b. In this

model, the magnetic structure, corresponding to the volcanic construction, is inferred to have a density of $2.67 \times 10^3 \text{ kg m}^{-3}$, whereas the overlaying terrains, thought to be mostly constituted of breccias, have a lower density.

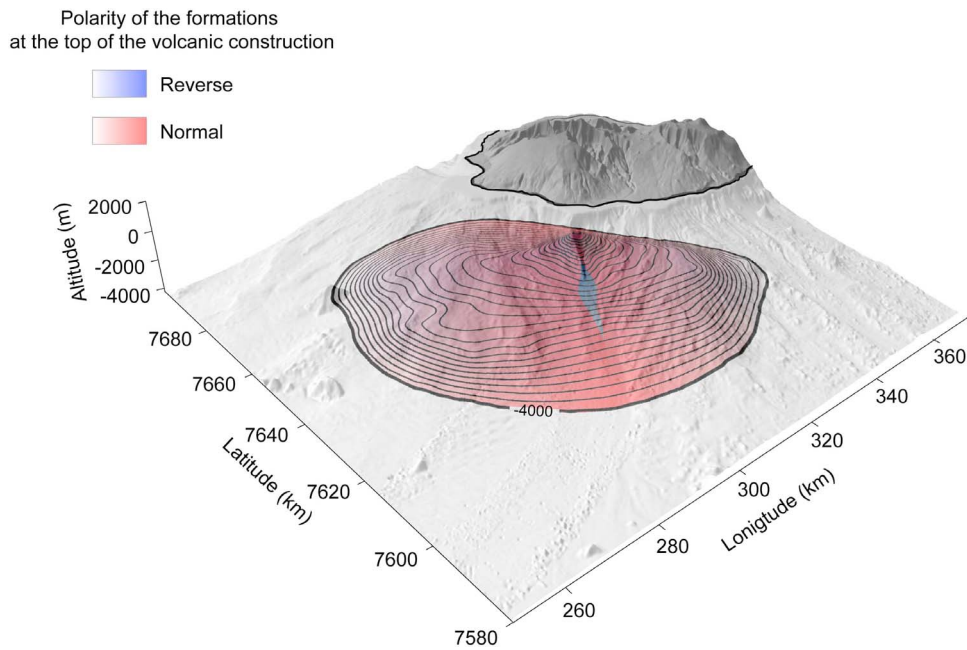


Figure 7. The 3-D morphology of the surface of the submarine ridge of Etang Salé reconstructed using the results of the $2\frac{3}{4}$ -D modeling. The contours represent the top of the magnetic structures obtained through modeling (contours interval of 50 m).

[58] This joint model provides information on the nature of the ridge and the surrounding volcanic constructions. The Etang Salé Ridge lies along the continuation of a subaerial rift zone-like structure (Figure 6a) and it bears morphological similarities with rift zones in similar context such as the submarine Puna Ridge [Smith *et al.*, 2002] along the continuation of the east rift zone of Kilauea volcano in Hawaii. The Puna Ridge is characterized by a high magnetization [Smith *et al.*, 2001] and the presence of a positive gravity anomaly explained by Leslie *et al.* [2004] by the presence of a dike swarm. The bathymetric feature of Etang Salé Ridge also exhibits high magnetizations, but the fact that it is surrounded and partially covered by low-density breccias and sediments precludes an unambiguous observation as to whether or not it is associated with a positive gravity anomaly. However, the presence of a large gravity anomaly that would be associated with a dense and large body of intrusions and cumulates, similar to the Grand Brûlé anomaly (Figure 2) can be ruled out. In summary, the morphology of the ridge and the interpretation of the magnetic and gravity data strongly suggest that there is a considerable offshore extension of the volcanic construction of La Réunion to the southwest of the island. This construction could be more or less organized around a long rift zone structure.

[59] The morphology of this volcanic construction has been reconstructed using the evenly spaced $2\frac{3}{4}$ -D magnetic models (Figure 7). The resulting structure presents an ellipsoidal shape about 80×90 km in dimension, centered on the rift zone. This result suggests that the constructed part of La Réunion volcanism extends much farther to the southwest than previously known, and that parts of this lateral volcanism predates the Brunhes-Matuyama magnetic reversal. Because of the strong arguments supporting continuity

between a Piton des Neiges rift zone, the Etang Salé Ridge and the buried part of the latter, the offshore construction is probably associated with lateral eruptions of the Piton des Neiges volcano. The alignment of the cones (Figure 6a) of recent ages (differentiated series) on the Piton des Neiges subaerial portion, and the magnetic interpretation clearly indicate that the Etang Salé rift zone has been active since before the Brunhes-Matuyama reversal for at least a few hundred thousand years.

4.5.4. Comparisons With the Seismic Data

[60] The Etang Salé Ridge is only partially covered on its eastern side by the seismic data from de Voogd *et al.* [1999]. Like in the case of the eastern submarine flank described above, we note a clear correlation between the location of the crustal bulging inferred by de Voogd *et al.* [1999] and that of the volcanic construction derived from our magnetic and gravity data interpretation. This can be clearly observed on Figure 8. Keeping in mind the uncertainties of both types of data, we note that the seismic V horizon follows the same trend as the inferred volcanic construction. We therefore suggest that in this area also, the lithospheric bulging proposed by de Voogd *et al.* [1999] beneath La Réunion does not exist, and instead represents the signature of the volcanic construction of La Réunion during its early stages.

4.6. Offshore Continuation La Montagne Massif

4.6.1. Geological Setting

[61] La Montagne Massif occupies the northern part of the island (Figure 9a) and is the oldest emergent part of Reunion Island, with ages up to 2.08 Ma [McDougall, 1971]. This pile of lava flows intersected by numerous dykes oriented N20°W has been interpreted as an ancient rift zone of Piton des Neiges [Chevallier and Vatin-Pérignon, 1982]. Beyond the coastal shelf, La Montagne Massif continues for 5 to

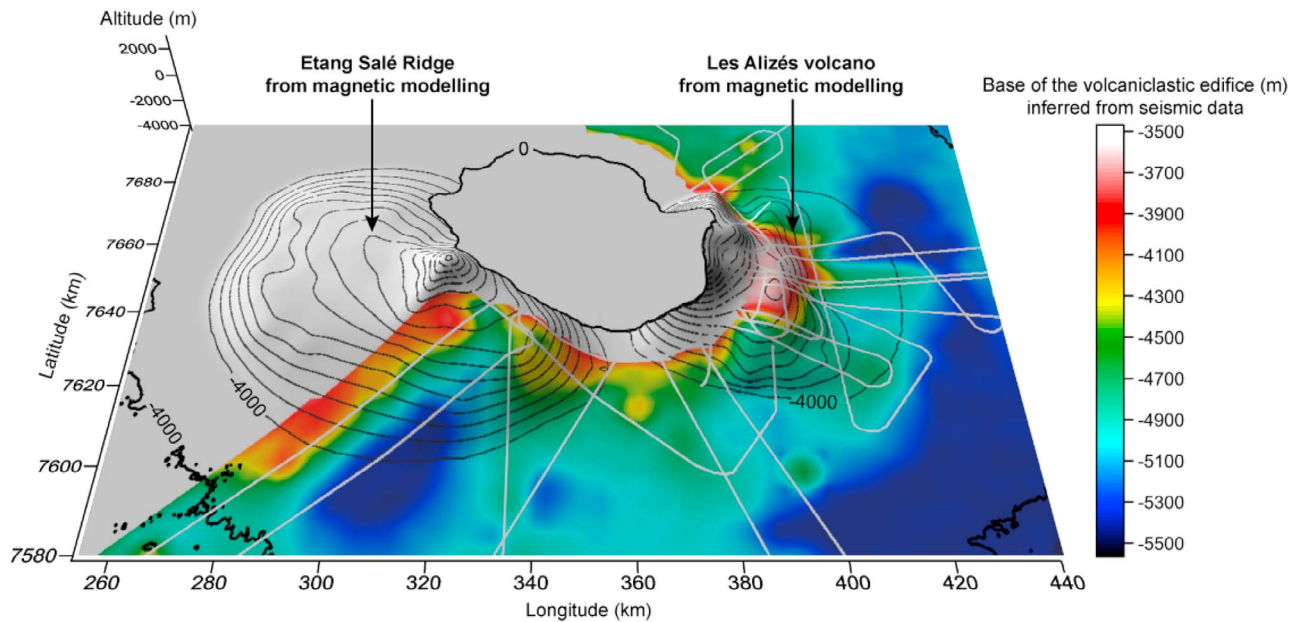


Figure 8. Comparison between the topography of the eastern and southwestern volcanic constructions inferred from the magnetic interpretation (shown in shaded relief and as 200 m interval contours) and the top of the V horizon of *de Voogd et al.* [1999] and *Pou Palomé* [1997], shown as color coded topography. The black line represents the coastline location, and the white lines locate the Reusis survey profiles.

10 km as a submarine promontory (Figure 9a), rising between 500 to 1200 m higher than the surrounding areas, for a lateral extent of 15 km in its proximal part and 5 km in its distal part.

4.6.2. Magnetic Study

[62] On land as well as offshore, La Montagne Massif is characterized by a well defined negative magnetic anomaly surrounded by two short-wavelength positive ones offshore

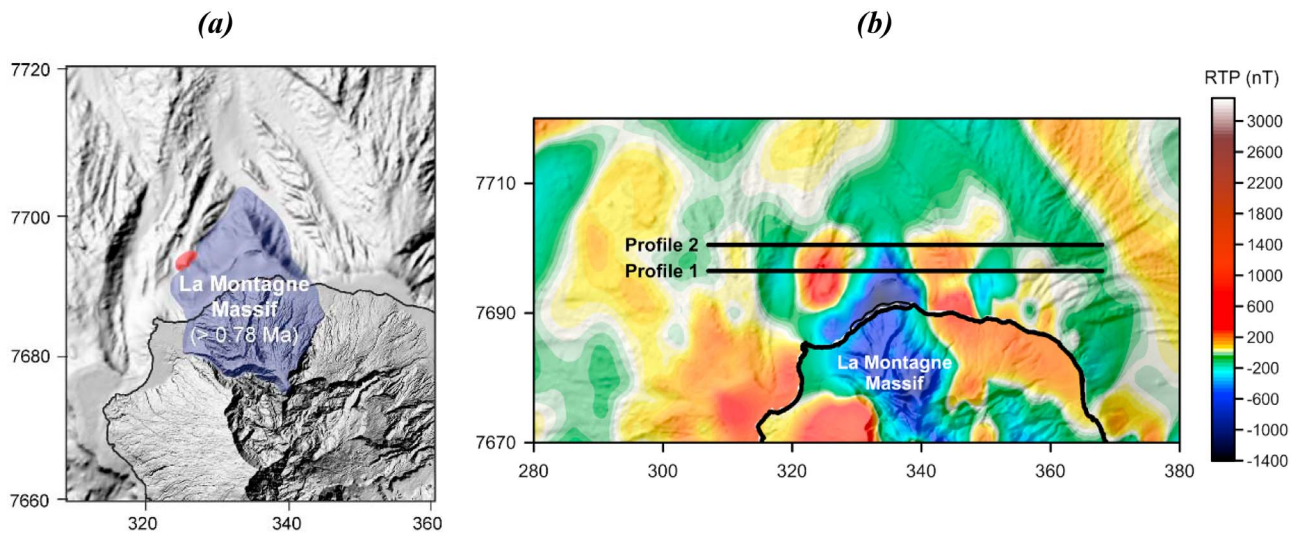
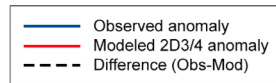
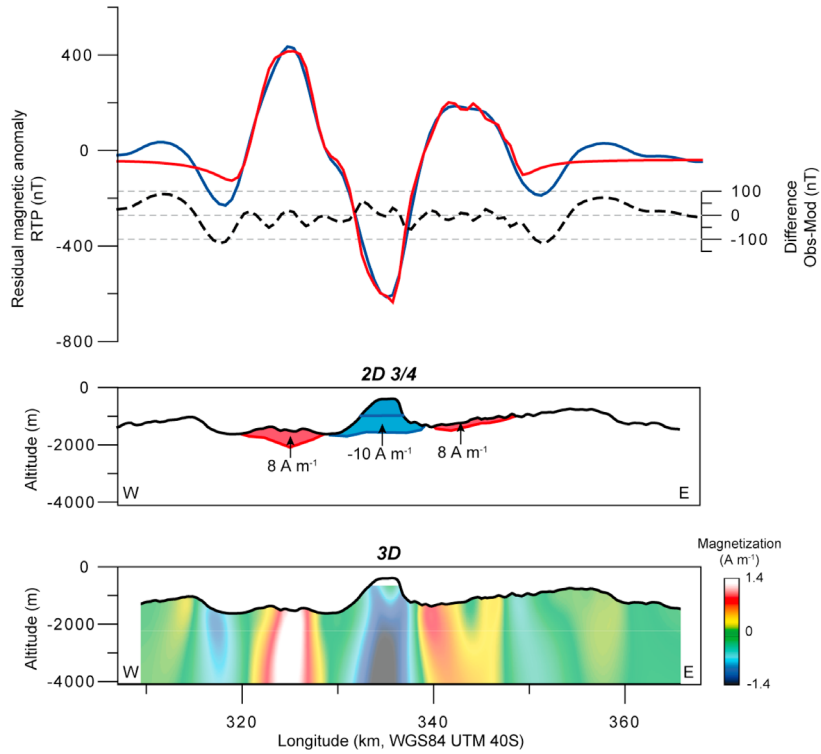


Figure 9. (a) Shaded topography and bathymetry of La Montagne Massif (in blue). The area in red corresponds to a fresh-looking cone. (b) Extract of the RTP magnetic anomaly map presented in Figure 3a showing the anomaly pattern associated with La Montagne Massif. (c) The $2\frac{3}{4}$ -D magnetic models along the profiles located in Figure 9b. The bottom sections show the 2-D magnetic models in the foreground, superimposed on the corresponding sections in the 3-D inversion model in the background. The 2-D structures are truncated at a distance of 7 km northward and 9 km southward from the profile direction for the first profile and at a distance of 3 km northward and 12 km southward for the second one. The normally and reversely magnetized structures are represented in red and in blue, respectively. Coordinates in kilometers (WGS84, UTM 40S).

(c)



Profile 1



Profile 2

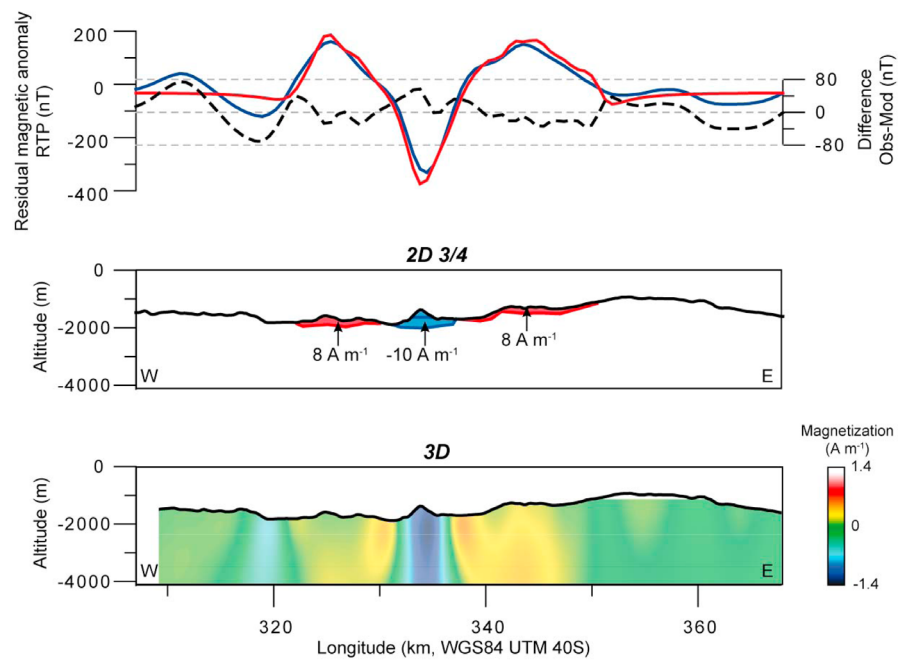


Figure 9. (continued)

(Figure 9b). The latter coincide with a cone-like relief to the northwest and to the littoral shelf and slope to the east. As described by *Lénat et al.* [2001], the negative anomaly is coherent with the reversed magnetization expected for the subaerial formations according to the published ages of La Montagne Massif. Conversely, the two positive anomalies suggest the existence of formations younger than the Brunhes/Matuyama reversal on the edges of La Montagne Massif.

[63] A 3-D inversion of the northern area has been carried out and 2^{3/4}-D models have been constructed along two E-W profiles practically orthogonal to the eastern boundary of the main structure (Figure 9b). The 3-D inversion (Figure 9b) produces a model with sharp limits between the reversely magnetized main structure and the two normally magnetized formations on the flanks. In the 2-D approach, the anomalies can be modeled with shallow, normally and reversely magnetized structures. We note that the magnetization contrasts here are appreciably lower than those observed in the two previously described areas.

[64] The magnetic models support the interpretation of the undersea promontory as the offshore continuation of La Montagne Massif. Beside this old massif, the surrounding normally magnetized structures suggest the emplacement of volcanic constructions younger than the Brunhes-Matuyama magnetic reversal. In particular, the positive anomaly to the northwest coincides with a small, cone-like relief, 3 km in diameter, which appears surprisingly noneroded, whereas all the other bathymetric features of the area exhibit signs of different degrees of erosion. However, the geological nature of this feature is not known.

4.6.3. Gravity Study

[65] Whereas the geological nature of the on land massif and the magnetic models suggest that La Montagne Massif is mostly formed by dense rocks (massive lava flows and intrusions), a negative gravity signature is observed on land as well as in its submarine continuation (Figure 10a). This pattern differs significantly from those observed for the eastern continuation of Piton de la Fournaise and the offshore part of the Etang Salé Ridge. It is well known that in oceanic islands delta-like lava are formed at the land-sea transition, composed mostly of pillow lavas, hyaloclastites and breccias [*Skilling*, 2002]. Therefore, their nature explains their gravity signature.

[66] A 2^{3/4}-D model has been built (Figure 10b) along the profile shown on Figure 10a, based on the model proposed by *Gailler et al.* [2009] for the gravity anomalies offshore of Piton de la Fournaise rift zones. In this model, the submarine formations are interpreted as hyaloclastites and pillow lavas, because their density is generally lower than that of massive lava flows [*Moore*, 2001], and can explain this gravity pattern, whereas their stable thermoremanent magnetization [*Harrison and Ball*, 1974] can account for the magnetic one.

[67] The offshore promontory is accordingly modeled as a low-density structure. The density increases from 1.8 to $2.4 \times 10^3 \text{ kg m}^{-3}$ from the seafloor to about 3200 m in depth to account for the lithostatic compaction [*Moore*, 2001], and a higher density ($2.9 \times 10^3 \text{ kg m}^{-3}$) is assigned to the subaerial part. However, to account for the gravity low above the subaerial part, the low-density hyaloclastite layer should probably extend on land beneath the sea level. Geologically,

this means that before La Montagne Massif emerged, it was mostly composed of hyaloclastites and pillow lavas, and then covered by the massive subaerial lava flows.

[68] The magnetic and gravity models cannot prove whether or not La Montagne Massif was a rift zone, but they indicate that the massif is composed of underwater facies below sea level, and that it does not extend as far from the coast as the eastern and southwestern structures described earlier. A 3-D reconstruction of the surface of the magnetic sources derived from the magnetic models (Figure 9b) is shown on Figure 11.

5. Structure of the Other Features of the Submarine Flanks

5.1. Geological Description

[69] The surface geology of the submarine flanks of La Réunion has been extensively described by *Oehler et al.* [2008]. The main features are four huge bulges covering the northern, eastern, southern and western submarine flanks from the coast to the oceanic seafloor (Figure 12a). For *Oehler et al.* [2008], they are predominantly built up of accumulations of products deriving from mass wasting processes. A quasi continuous shelf is observed near the coast between sea level and approximately -100 m in depth (Figure 12a), with an average width of 2–3 km around Piton des Neiges, but narrower around Piton de la Fournaise and disappearing altogether to the east. *Oehler et al.* [2008] associate this shelf with past sea level lows. In addition, *Oehler et al.* [2008] describe a few small volcanic constructions on the submarine flanks. Some of them, located near the coast, can be associated with La Réunion volcanism, whereas others, located on the lower parts of the flanks, are constructions belonging to the oceanic plate protruding above the submarine flank formations.

5.2. Description of the Gravity and Magnetic Anomalies of the Submarine Flanks

[70] Each type of bathymetric feature defined by *Oehler et al.* [2008] is associated with a particular gravity signal (Figure 12a). The coastal shelf corresponds to a negative Bouguer anomaly belt at the land-sea transition and also to a belt of short-wavelength magnetic anomalies (Figure 3a). The submarine flanks are also characterized by negative Bouguer anomalies coinciding with the four topographic main bulges. As previously mentioned, because of their brecciated nature [*Oehler et al.*, 2008], the submarine flanks are virtually “transparent” from a magnetic point of view, exhibiting no particular magnetic signal except in the areas analyzed above and to the west where the fan-shaped gravity low coincide with an approximately equivalent fan-shaped magnetic high. In this section, we will consequently use the gravity data alone to study the coastal shelf and the main submarine bulges.

5.2.1. Modeling and Interpretation of the Gravity Anomalies Associated With the Coastal Shelf

[71] The negative Bouguer anomaly belt around the emerged complex suggests the presence of formations less dense than the density correction of $2.67 \times 10^3 \text{ kg m}^{-3}$, but the associated magnetic signature indicates the presence of undisturbed volcanic constructions. 2^{3/4}-D models have been

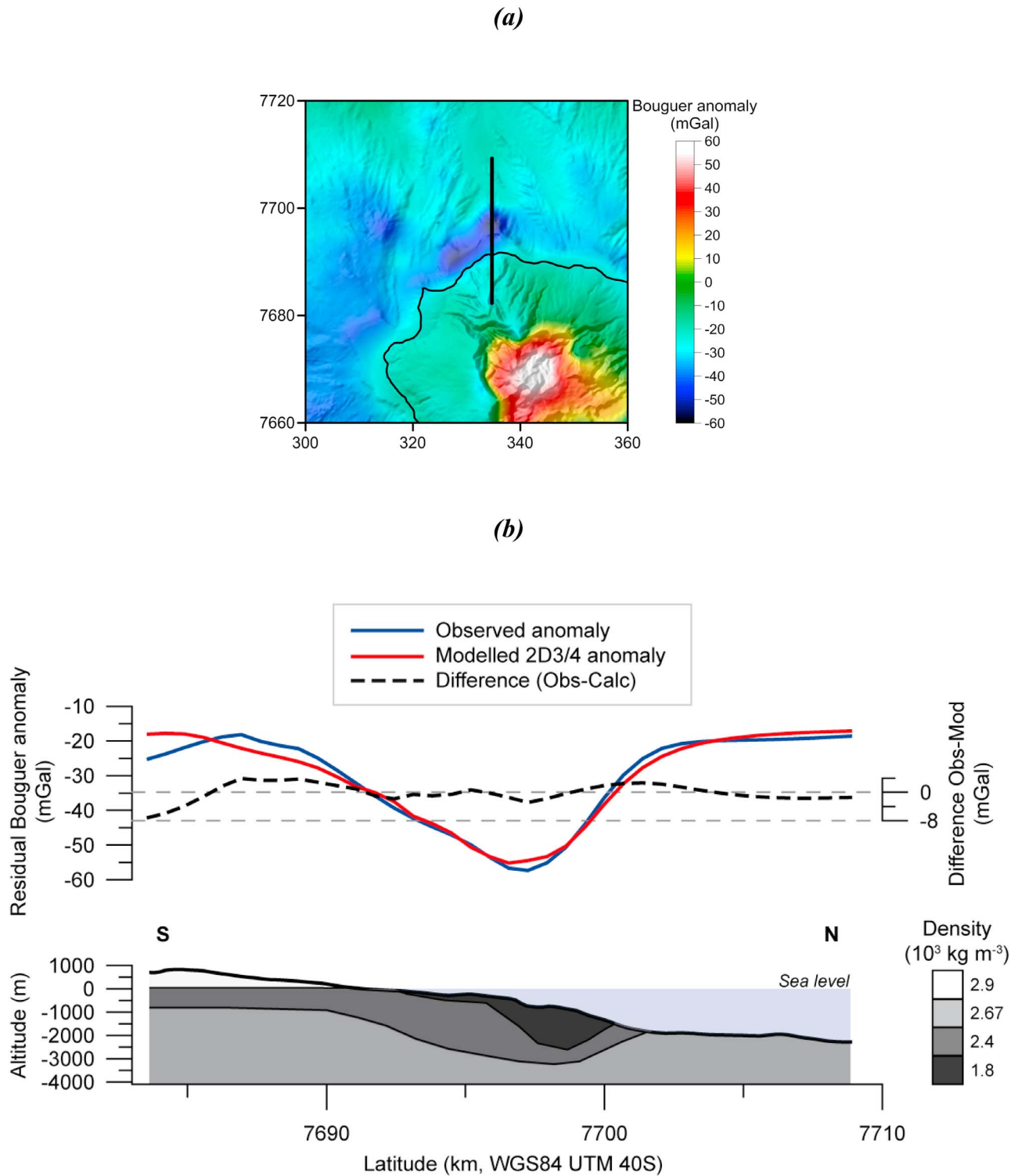


Figure 10. (a) Location of the study profile on an extract of the Bouguer anomaly map computed for a density correction of $2.67 \times 10^3 \text{ kg m}^{-3}$, centered on the northern part of La Réunion. (b) The $2\frac{3}{4}$ -D gravity model on the north to south profile 1 shown in Figure 10a. The inferred layers are truncated at a distance of 8 and 12 km in the eastern and western profile directions, respectively.

built to study these structures. As in the case of the offshore continuation of the Piton de la Fournaise rift zones and La Montagne Massif, the shelf can be assumed to be essentially built of hyaloclastites and pillow lavas. The coastal shelf is

therefore modeled as a stratified structure (Figure 12b), with density increasing from 1.8 to $2.0 \times 10^3 \text{ kg m}^{-3}$ with depth. Its vertical extent ranges from 2000 m (profile 1 on Figure 12b) to 600 m (profile 2 on Figure 12b).

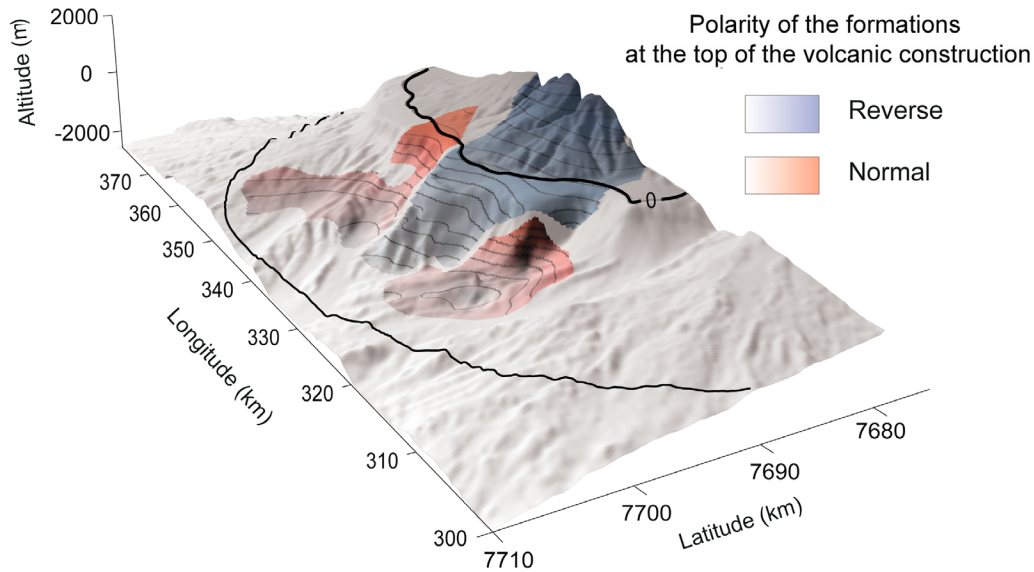


Figure 11. The 3-D morphology of the offshore continuation of La Montagne Massif surface from the results of the 3-D inversion and the 2 $\frac{3}{4}$ -D magnetic modeling. The black line drawn offshore represents the maximum magnetic vertical gradient extent in the northern area.

[72] The gravity models support the interpretation of the coastal shelf as deltas mainly composed of hyaloclastites and pillow lavas. This interpretation is also coherent with a narrower shelf around the young coasts of Piton de la Fournaise, where paleocoasts formed during low sea level period have been resurfaced by subsequent lava flows. The fact that the negative pattern is less marked in the Etang Salé Ridge area may be related to the specific structure of this zone, as described above.

5.2.2. Modeling and Interpretation of the Gravity Anomalies Associated With the Submarine Bulges

[73] As previously described, the four main bathymetric bulges are associated with negative gravity anomalies (Figure 12a). This observation is in agreement with the interpretation of *Oehler et al.* [2008], who consider the bulges as accumulations of products derived from mass wasting. We have therefore assigned low density values to the bulges from the surface to the presumed base of the volcanic system at -4000 m, except in the areas where we have inferred the presence of volcanic constructions.

[74] A 3-D inversion has been carried out, and 2-D models constructed for each bulge. The 3-D models from inversion mostly show lateral variations of density within the bulges, but have a poor vertical resolution of the structures. For each bulge, two or three parallel profiles running perpendicular to the mean slope of the bulges have been modeled.

[75] Figure 12c shows a 2-D model example obtained for a north-south profile on the eastern bulge. The anomaly is correctly fitted for a density of $2.2 \times 10^3 \text{ kg m}^{-3}$ for the overall bulge. However, in order to fit the shorter-wavelength anomalies, lateral contrasts of density are required. In the model, the contrasts are created by shallow structures with a lower density than that of the overall bulge. The rationale is to consider that the surface deposits are less compacted than the deeper ones.

[76] For each bulge, good correlations appear between the geological units defined by *Oehler et al.* [2008] and the distribution of the density values in the models. The interpolation of the density values along the individual gravity profiles (Figure 13) illustrates this correlation on the map. However, not all the units from *Oehler et al.* [2008] have a corresponding gravity signature. This is easily explained if we consider that on one hand, some of the units are very small, and, on the other hand, that different units may have similar or even close densities. Some units, or set of units, can be clearly distinguished according to their density (Figure 13b). The lower density range is associated with some large units (e.g., GN2, GN4 for the northern bulge, GE2a, GE2b for the eastern bulge, GS1a, GS1b for the southern bulge and GW1 for the western bulge), whereas moderate densities correlate with channels separating larger units (e.g., GE1b) and sedimentation zones (e.g., GS2a and GS2b). On the contrary, some units are associated with higher densities (e.g., GE3, GN1 and GN3), which also often correspond to units exhibiting large emergent blocks, a chaotic topography and a visible, thin sedimentary blanket [*Oehler et al.*, 2008]. These may represent denser mass-wasting deposits with a high content of megablocks. We also note that the western submarine bulge is significantly more homogeneous, in terms of density, than the three others.

6. Discussion and Conclusions

[77] Like for many volcanic islands, the submarine flanks of La Réunion represent a far greater surface and volume than the emerged part. Previous studies of the undersea parts of La Réunion and other volcanic islands have mostly focused on the surface products, using bathymetry, acoustic images and sampling. The new aspect of the work presented here is to use gravity and magnetic signals to extend the

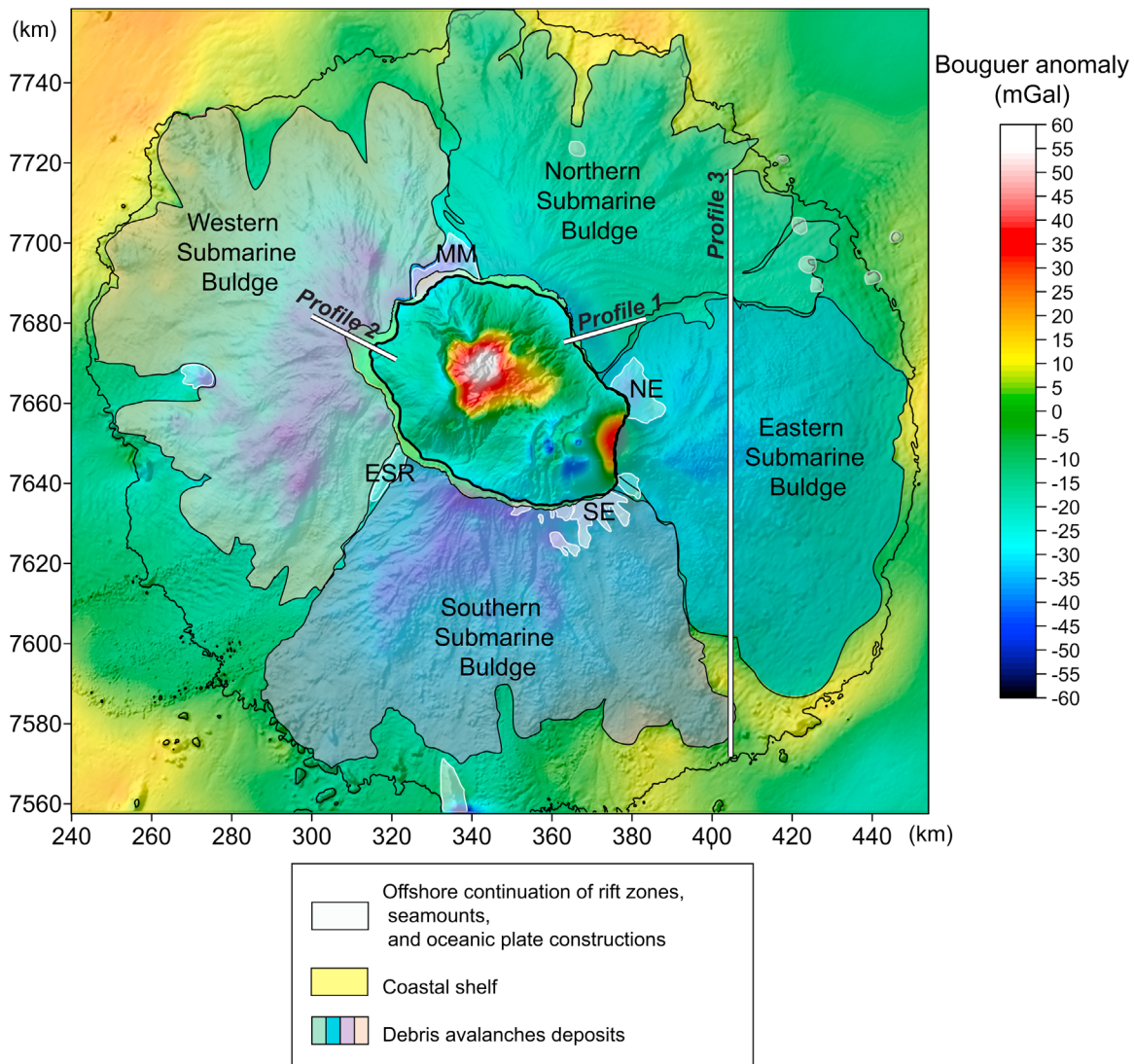


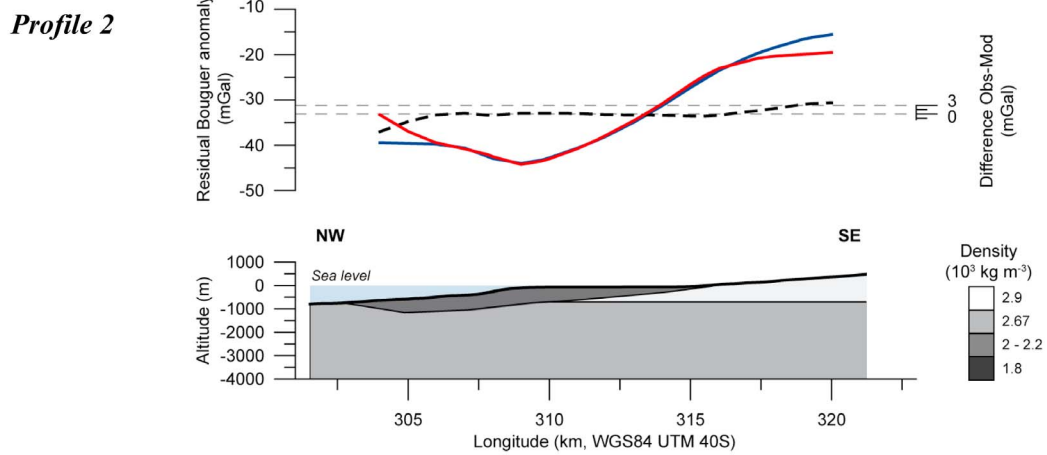
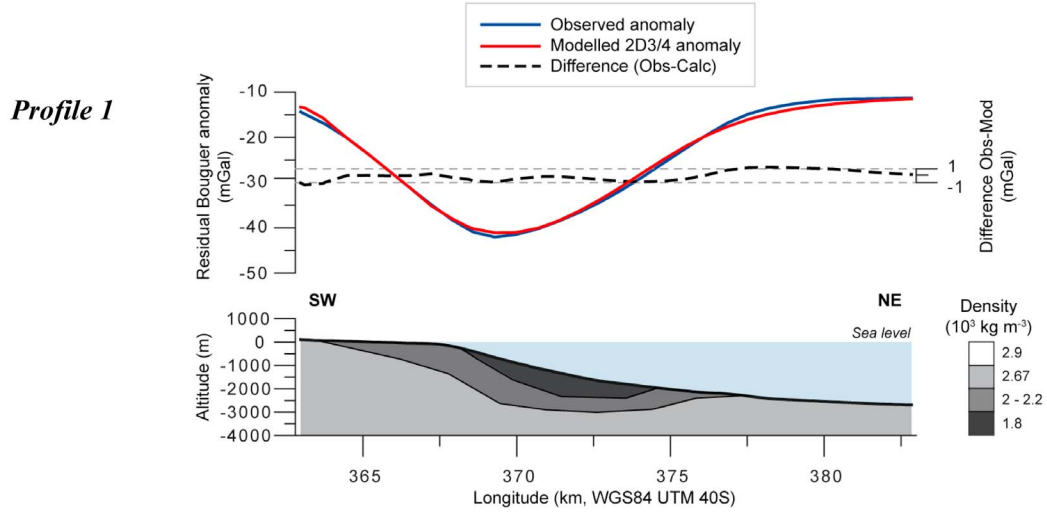
Figure 12. (a) Interpretative distribution of the anomaly sources superimposed onto the Bouguer anomaly map presented in Figure 2 (correction density of $2.67 \times 10^3 \text{ kg m}^{-3}$). The main features are presented: the coastal shelf, the northern, eastern, southern and western submarine bulges, and the offshore volcanic constructions (NE and SE, offshore continuation of the NE and SE Piton de la Fournaise rift zone, respectively; ESR, Etang Salé Ridge; MM, La Montagne Massif). Coordinates in km, WGS84 UTM 40S. (b) The $2\frac{3}{4}$ -D models of the coastal shelf along the profiles located in Figure 12a; the layers are truncated at a distance of 20 km in the northwestern and 13 km in the southeastern direction along profile 1 and 26 km in both northwestern and southeastern directions along profile 2. (c) The 2-D model of the eastern submarine bulge along the profiles shown in Figure 12a.

investigation at depth. Three major types of results have been obtained: (1) the discovery of unknown huge offshore extent of the volcanic constructions in two areas; (2) the validation of the nature of the four bulges as predominantly breccias deposits; and (3) the presence of a belt of hyaloclastite and pillow lava around the island.

[78] The magnetic data have been instrumental in discovering the offshore extent of the volcanic constructions of La Réunion. The presence of both normal and reverse, short- to medium-wavelength, anomalies around the emerged part of the island, argues for formations that have kept their

thermoremanent component which is the undisputable proof that coherent volcanic constructions are present beneath the debris avalanches deposits and sediments covering the submarine flanks (Figure 3). These constructions lie, at least in part, in the continuation of the island ones, and their magnetic signature differentiates them clearly from the features of the underlying oceanic crust. Huge, previously unrecognized, volcanic constructions, extending tens of kilometers from the seashore, have thus been evidenced to the east (the Alizés zone) and southwest (the Etang Salé zone) of the island and represent a substantial surface of the construction of La Réunion.

(b) Coastal Shelf



(c) Eastern Bulge

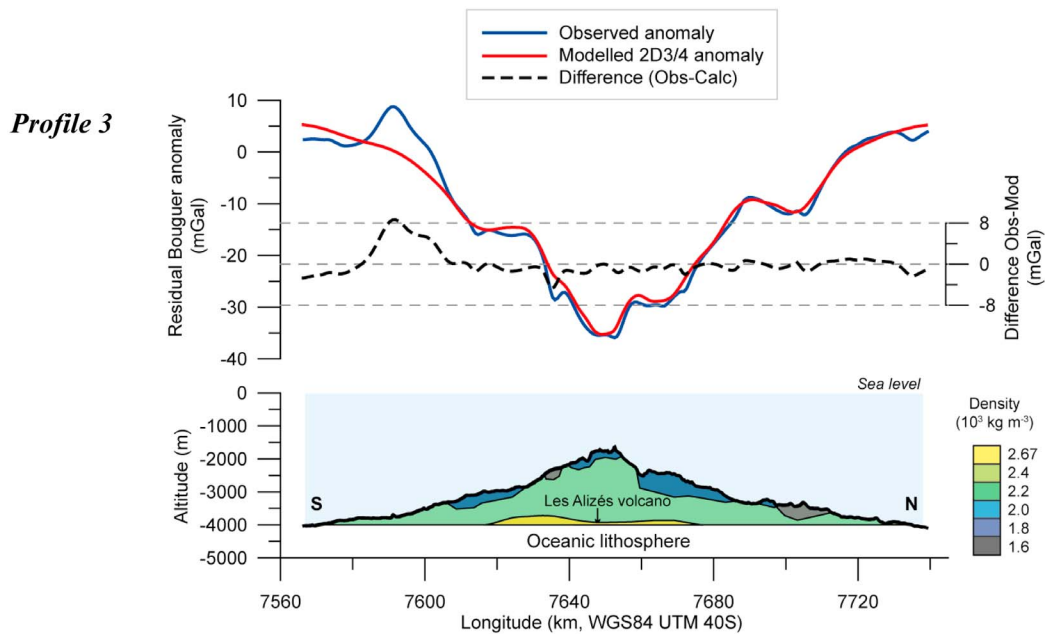


Figure 12. (continued)

(a)

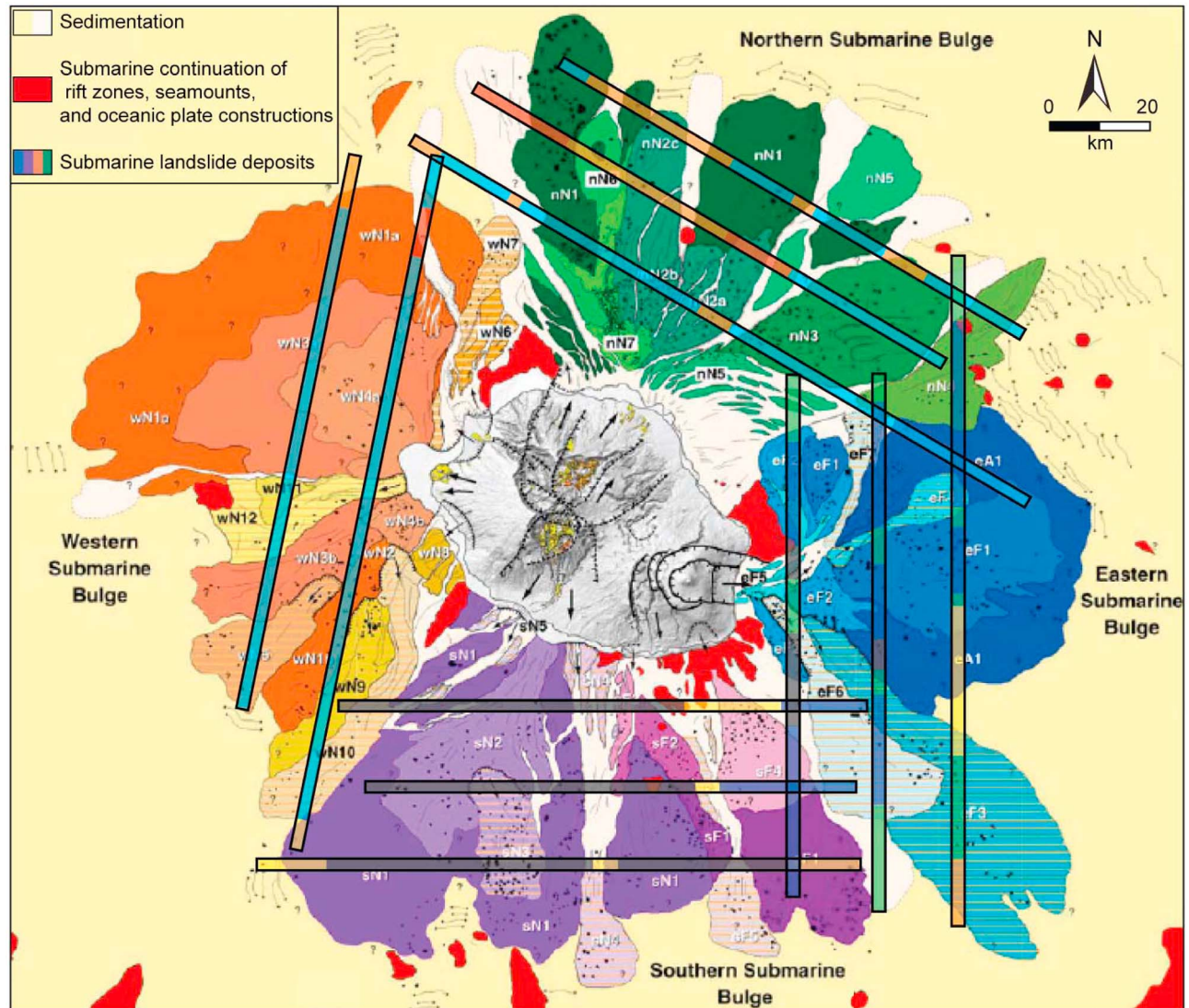


Figure 13. (a) Geological map of the submarine flanks of Reunion Island, from *Oehler et al.* [2008]. (b) Inferred 2-D density distribution at the surface of the submarine flanks, based on the modeling along different profiles and the correlations with the geological units defined by *Oehler et al.* [2008]. The labels (e.g., GE) refer to the gravity (G) units of north (N), east (E), south (S) and west (W). The numbers and their letter index (e.g., 1b) specify units and subunits.

[79] The Alizés submarine construction seems to be located around a major hypovolcanic complex located near the seashore (Figure 4), whereas Etang Salé zone cannot be associated with a similar volcanic center, since no strong positive gravity anomaly argues for the presence of a dense intrusive core. It seems more likely to be at least partly controlled by an elongated structure which bears volcanic rift zone characteristics. The Etang Salé zone would thus be a now concealed extension of Piton des Neiges volcano. The inferred submarine volcanic rift zone coincides locally with a prom-

inent submarine ridge and connects with a line of subaerial cones younger than 0.43 Ma (Figure 6a). The negative polarity of the magnetic anomaly associated with the inferred rift zone indicates that it was mostly built before the Brunhes-Matuyama magnetic reversal (0.78 Ma), but the magnetic models suggest that the upper part of this inferred rift zone might be composed of younger, normally magnetized, rocks. Thus, considering that the submarine rift zone and the on land alignment of cones belong to the same structure, the latter would have been active for a long period of time.

(b)

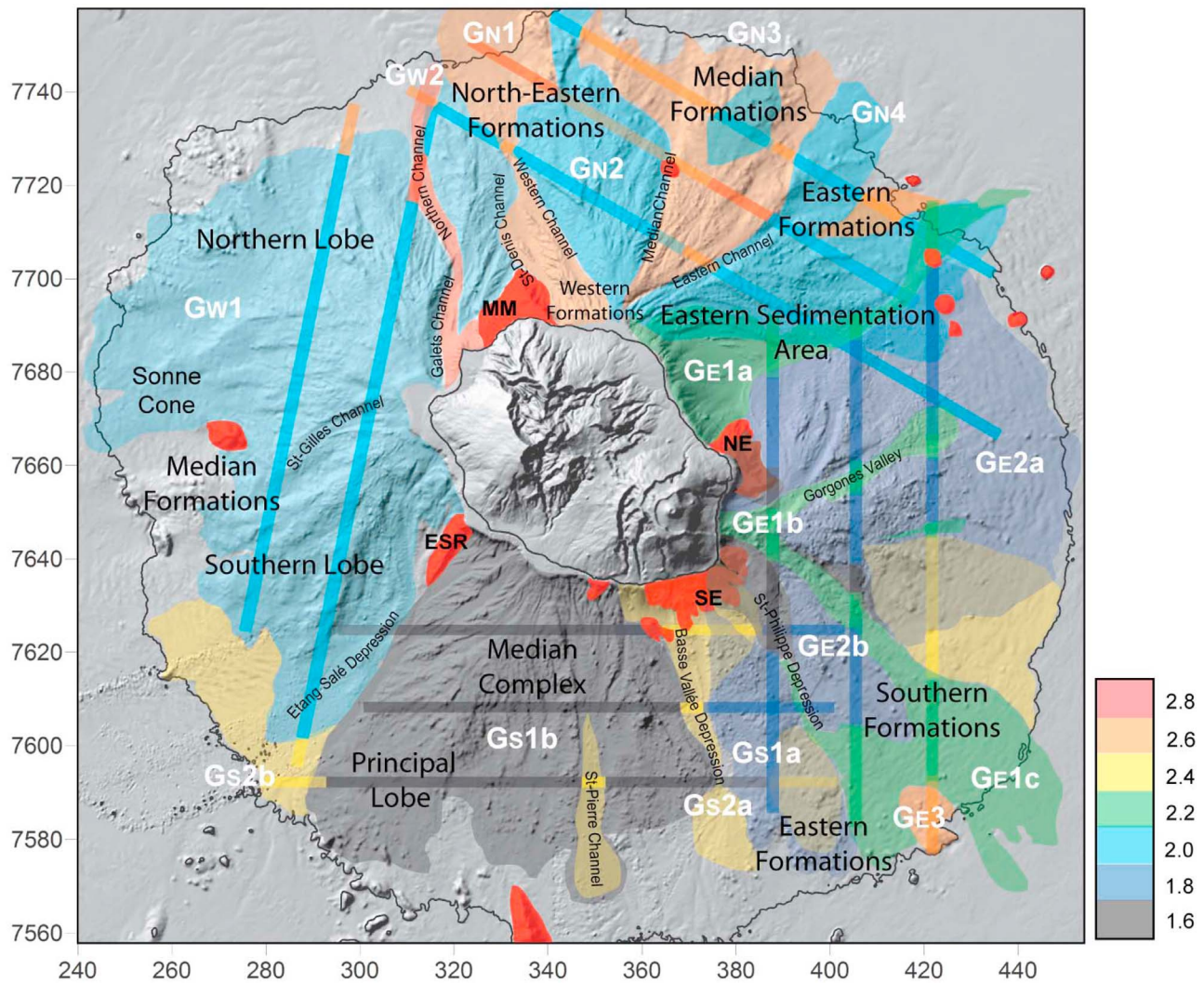


Figure 13. (continued)

[80] The depth of the roof and the magnetic polarization of both construction show that they were mostly built during early phases of La Réunion volcanism. However, like most of the volcanic system, they could also have been partially destroyed by mass wasting processes [Oehler *et al.*, 2008]. For Les Alizés, the important role of mass wasting is clear. The top of the hypovolcanic complex is located about 1000 m beneath the present surface [Rançon *et al.*, 1989] and no outcropping geological formation can be linked to the edifice associated with the complex, even if some submarine features near the coast might belong to Les Alizés. In regard to the long-time evolution, recurrent volcano-tectonic and erosional processes associated with the evolution of oceanic islands, we consider that a large part of Les Alizés volcano

should have been destroyed by landslides. In addition, Oehler *et al.* [2008] inferred that part of the submarine debris avalanche deposits to the east can be associated with landslides from the Les Alizés volcano. Etang Salé zone is almost entirely buried beneath the south and west submarine bulges of debris avalanches and sediment deposits [Oehler *et al.*, 2008]. The Etang Salé Ridge protrudes into the saddle between the two bulges (Figure 6a) and could be a remnant relief isolated between zones affected by landslides. Elsewhere, the constructions extend only about 10 to 15 km from the seashore, forming the 10–20° natural slope of the constructions observed on land.

[81] The morphology of the submarine constructed part of La Réunion can be reconstructed on the base of the

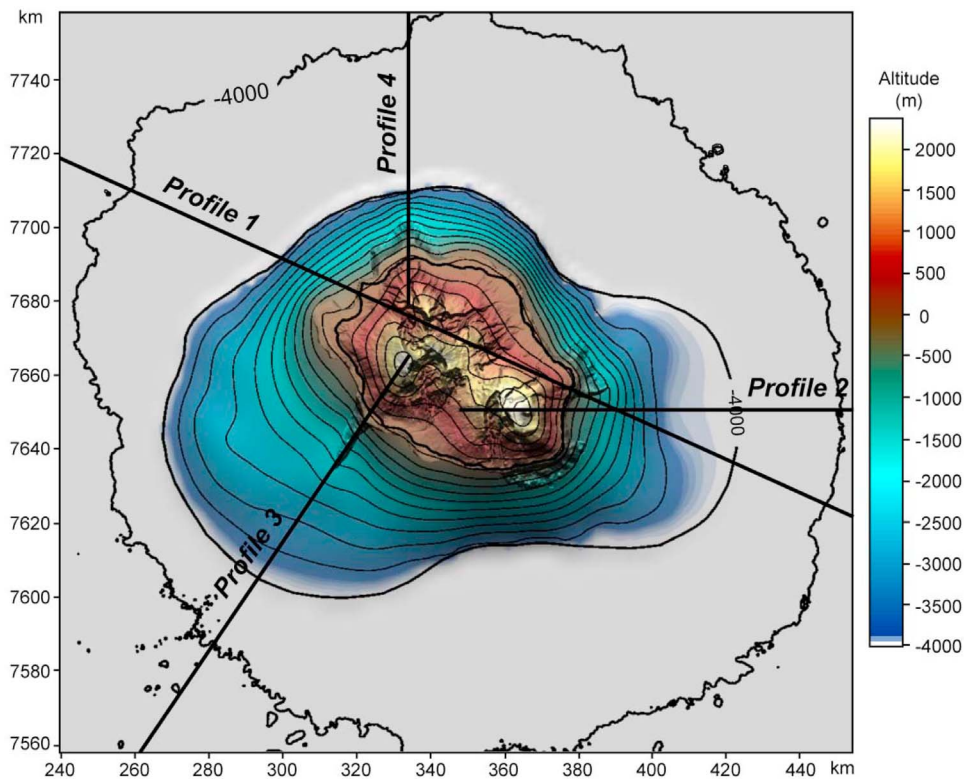


Figure 14. The 3-D morphology of the constructed volcanic edifice integrating the on-land part and the submarine parts recognized in this study. The present-day shoreline and the present-day -4000 m contours are shown with black lines. Coordinates in km, WGS84 UTM 40S.

magnetic and gravity analyses and models (Figure 14). The short- to medium-wavelength anomaly belt has been used to define the maximum extent of the offshore constructed part of the edifice. The reconstructed edifice exhibits a dramatically different shape than that of the emerged part of La Réunion. It has an ellipsoidal shape with two main outgrowths toward the east and the southwest, extending about 200 km along the NE direction and 160 km along the NW direction. On Figure 15, selected sections emphasize the new structures suggested by our models. Note that in Figure 15, the Piton des Neiges and the Alizés hypovolcanic dense complexes are based on a separate work by Gailler and Lénat [2010].

[82] The discovery of large offshore extensions of the La Réunion volcanic construction has brought our attention to the previous interpretation of seismic horizons by *de Voogd et al.* [1999] and *Pou Palomé* [1997]. We demonstrate that the seismic horizons are coincident, especially to the east (Figure 16) and to the southwest of the island, with the top of the two main volcanic constructions derived from our magnetic model. The general magnetic scheme is also appropriate for the other areas around the island. This interpretation challenges the previous hypothesis of a general bulge of the oceanic crust beneath La Réunion. In our interpretation, we see only the slope or offshore extensions of the volcanic constructions.

[83] The coastal shelf around La Réunion is associated virtually everywhere with a negative Bouguer anomaly. In

some locations, the shelf is associated with prominent magnetic anomalies, as in the case of the Piton de la Fournaise rift zones offshore continuation to the east, and in the continuation of La Montagne Massif to the north. The eastern anomaly has been already discussed and interpreted by *Gailler et al.* [2009], and we propose a model accounting for the strong magnetization and low density of La Montagne Massif both offshore and on land. The offshore magnetic and gravity pattern are explained by the presence of pillow lavas and hyaloclastites (Figure 15, profile 4). On land, we infer that the subaerial pile of lava flows rests on a low-density material series that are also probably pillow lavas and hyaloclastites. We also note that a small, normally magnetized cone-like relief, lies on the offshore tip of La Montagne Massif. This was not expected, because La Montagne Massif is built by the oldest known rocks of La Réunion (about 2.1 Ma).

[84] Finally, the good gravity and magnetic coverage of the submarine flanks has allowed us to study the structure of the four major bulges described by *Oehler et al.* [2008]. Their magnetic and gravity signatures strongly support their nature as being essentially composed of breccias with a weaker magnetization and a lower density than those of the volcanic constructions. In detail, the gravity interpretation suggests the presence of lateral variations of density within the bulges, with some correlations with the units of the geological map established by *Oehler et al.* [2008] as well as with surface facies.

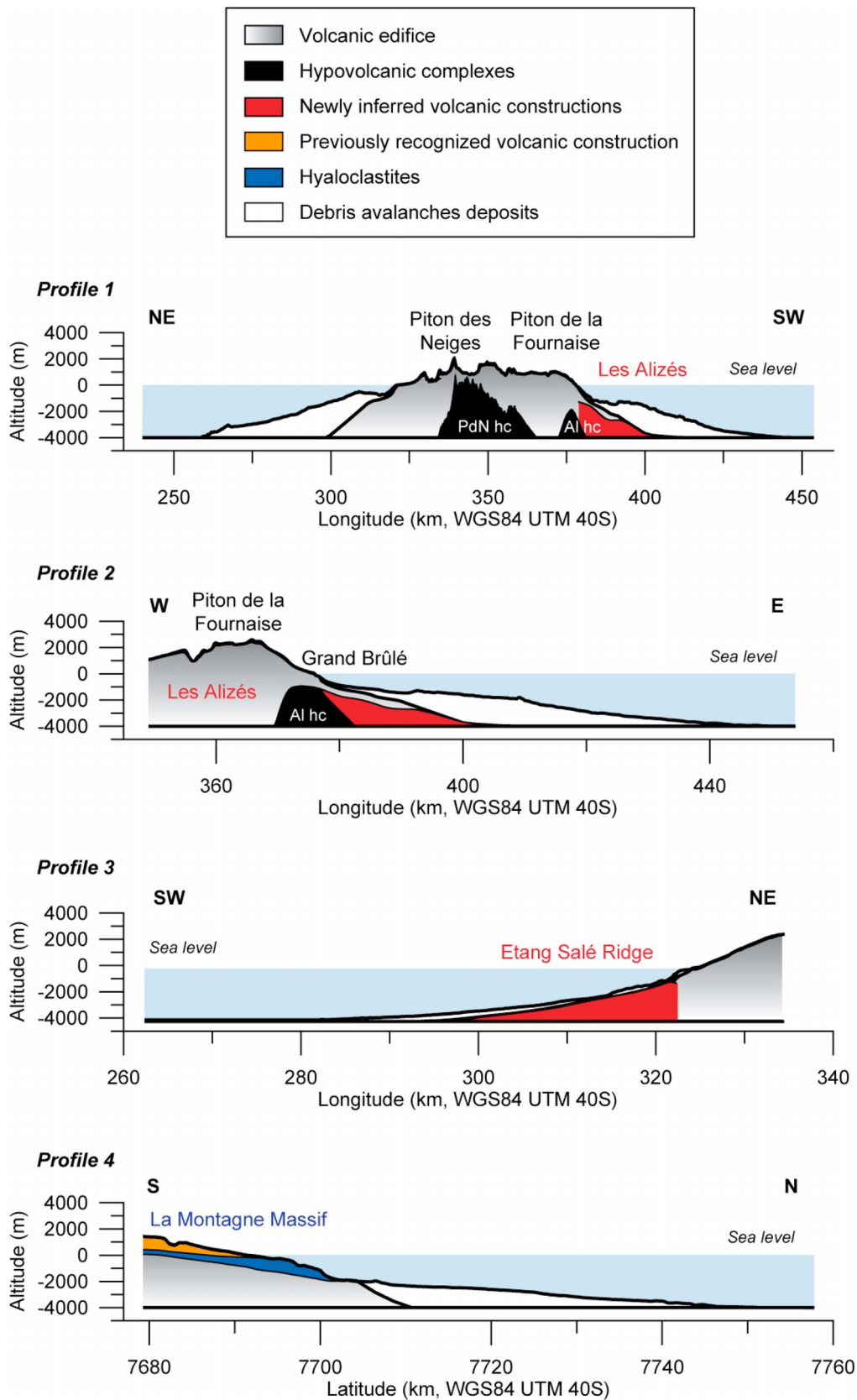


Figure 15. Slices from the 3-D model presented in Figure 14 along the main structures discussed in the text. The submarine volcanic constructions presented in this study (i.e., Les Alizés Volcano, Etang Salé Ridge and La Montagne Massif) are underlined. The hypovolcanic complexes of Les Alizés Volcano (Al hc) and Piton des Neiges (PdN hc) are described by Gailler and Lénat [2010].

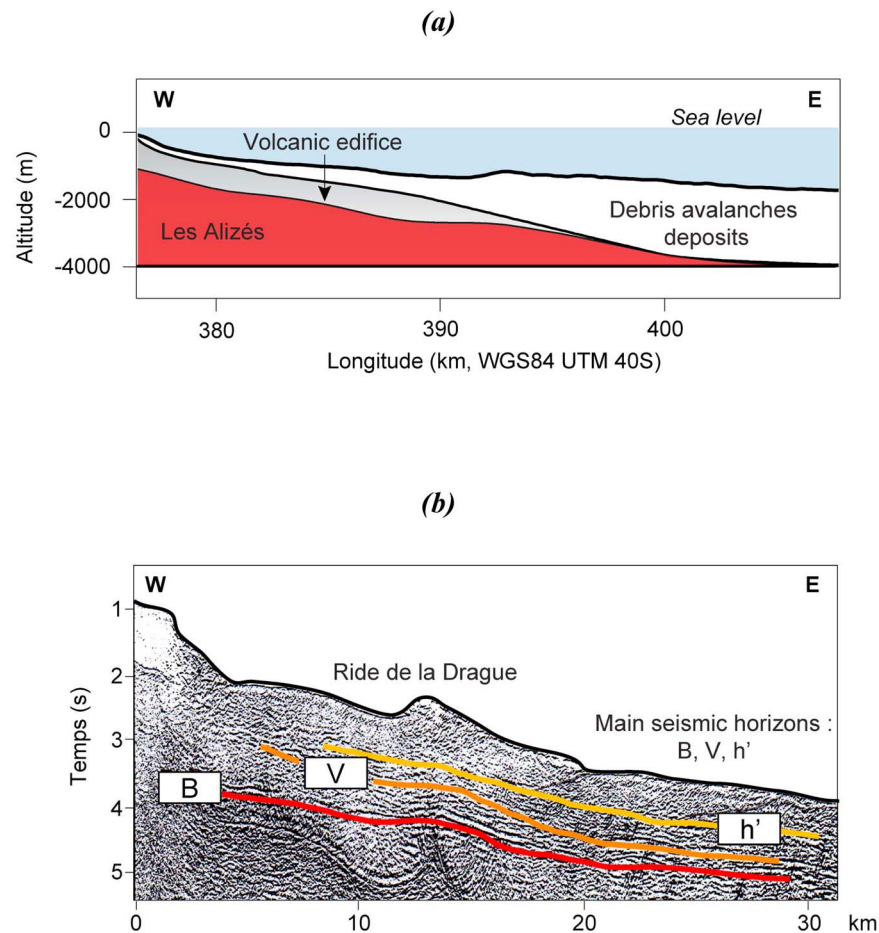


Figure 16. (a) Slice from the 3-D magnetic model across Les Alizés Volcano, extracted from Figure 15 (profile 2). (b) Portion of the seismic profile R7w: V is the base of the volcanoclastic edifice, B is the top of the oceanic basement, and h' is an intraedifice reflector.

[85] **Acknowledgments.** This work has benefited from data acquired by numerous scientific projects. We thank the captains and crew and their scientific leaders: Paul Beuzard (Hydroamsterdam, 1984), Peter Stoffers (SO87, 1993), Philippe Patriat (Gallieni, 1995), Christine Deplus (FOREVER, 2006), Bruno Savoye and Patrick Bachèlery (ERODER 1, 2006 and ERODER 2, 2007). We have a special thought for Bruno Savoye, who tragically passed away in 2008. The paper has benefited from helpful and constructive reviews and comments from Isabel Blanco Montenegro and Gareth Ito.

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