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A new model for the evolution of the volcanic island of Réunion (Indian Ocean)

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Abstract. The island of Réunion has been studied using data from airborne and shipborne magnetic surveys. The subaerial history of Réunion spans the last 2.1 million years. The Brunhes-Matuyama geomagnetic reversal enables differentiation of volcanic rocks older and younger than 0.78 Ma. The lower submarine flanks are poorly magnetized and are interpreted as landslide deposits. The core of the island is composed of highly magnetized rocks. Piton des Neiges volcano is composed mostly of rocks older than 0.78 Ma. Only its western flank and central area include thick piles of younger rocks. Piton de la Fournaise is a highly and normally magnetized edifice, but its northern and eastern flanks are underlain at shallow depth by reversely magnetized formations. The latter are regarded as remnants of Les Alizés volcano, associated with the Grand-Brûlé hypovolcanic complex. At the Matuyama-Brunhes transition the island was composed of at least two main volcanoes (Piton des Neiges and Les Alizés) and perhaps also of a third old volcano (Takamaka) at the center-north of the island. Piton de la Fournaise grows on the flank of Les Alizés and is a relatively young focus of volcanism. These volcanoes have had successive phases of construction and destruction. The analysis of magnetic anomalies over Réunion was decisive in defining a new coherent model for the evolution the island.

1. Introduction

Oceanic islands and seamounts are volcanic constructions that usually evolve over of a few million years and are controlled by a complex interplay of geodynamic factors (hot spot displacement, regional tectonic stresses, and variations in magma production and magma composition) and volcanic processes (intrusion, eruption, formation of magma chambers, caldera subsidence, and flank collapse). Usually, only the last stages of volcano development can be observed and sampled directly, leaving most of their geologic history to be inferred by indirect methods.

To overcome this inherent difficulty, two main approaches are commonly used. The first involve study of a group of edifices showing different stages of evolution. The best illustration is provided by the Hawaiian-Emperor Chain, which exhibits a succession of more than 100 volcanoes at different stages of evolution, from a young, actively growing seamount (Loihi) to old, extinct, eroded, and sunken seamounts. Syntheses based on observations at the different sites allow general evolutionary hypotheses to be derived [e.g., Peterson and Moore, 1987]. The second approach uses geophysical methods to image the internal structure of a given seamount or island in order to infer its structural evolution. Numerous and various geophysical studies have thus been carried out, mostly on islands but also on seamounts (see, e.g., *Hammer et al.* [1994] and *Gee et al.* [1988] for studies of Jasper Seamount in the Pacific Ocean).

We have studied the structure of Réunion island, in the Indian Ocean, using data from magnetic surveys. The preponderance of the thermoremanent component of the magnetization of the volcanic rocks enables to locate areas that are predominantly composed of formations either younger or older than the Brunhes-Matuyama geomagnetic reversal (0.78 Ma). First, from the analysis of negative anomalies near the seashore, we demonstrate the presence of reversely magnetized formations beneath the two subaerial volcanoes of the island. Next, we delineate the main structures corresponding to volcanic constructions before and after the Brunhes-Matuyama geomagnetic reversal. We then derive a coherent model for the evolution of the island by integrating the magnetic results with other geological and geophysical data. The resulting geologic synthesis leads us to (1) reconsider previous evolution models for Piton des Neiges and Piton de la Fournaise volcanoes, (2) document the presence of a third major volcano (Les Alizés) and to reinforce the gravity and seismic evidence for the presence of a fourth volcano (Takamaka), (3) delineate major source areas for large-scale mass-wasting events during growth of the island, (4) propose a possible explanation for the occurrence of the shallow eastward-directed landslides of Piton de la Fournaise, and (5) explain the development of the present-day rift zones of Piton de la Fournaise and the westward migration of its center.

2. Geological and Structural Setting

Réunion island is located in the southernmost part of the Mascarene Basin (Indian Ocean), 800 km east of Madagascar

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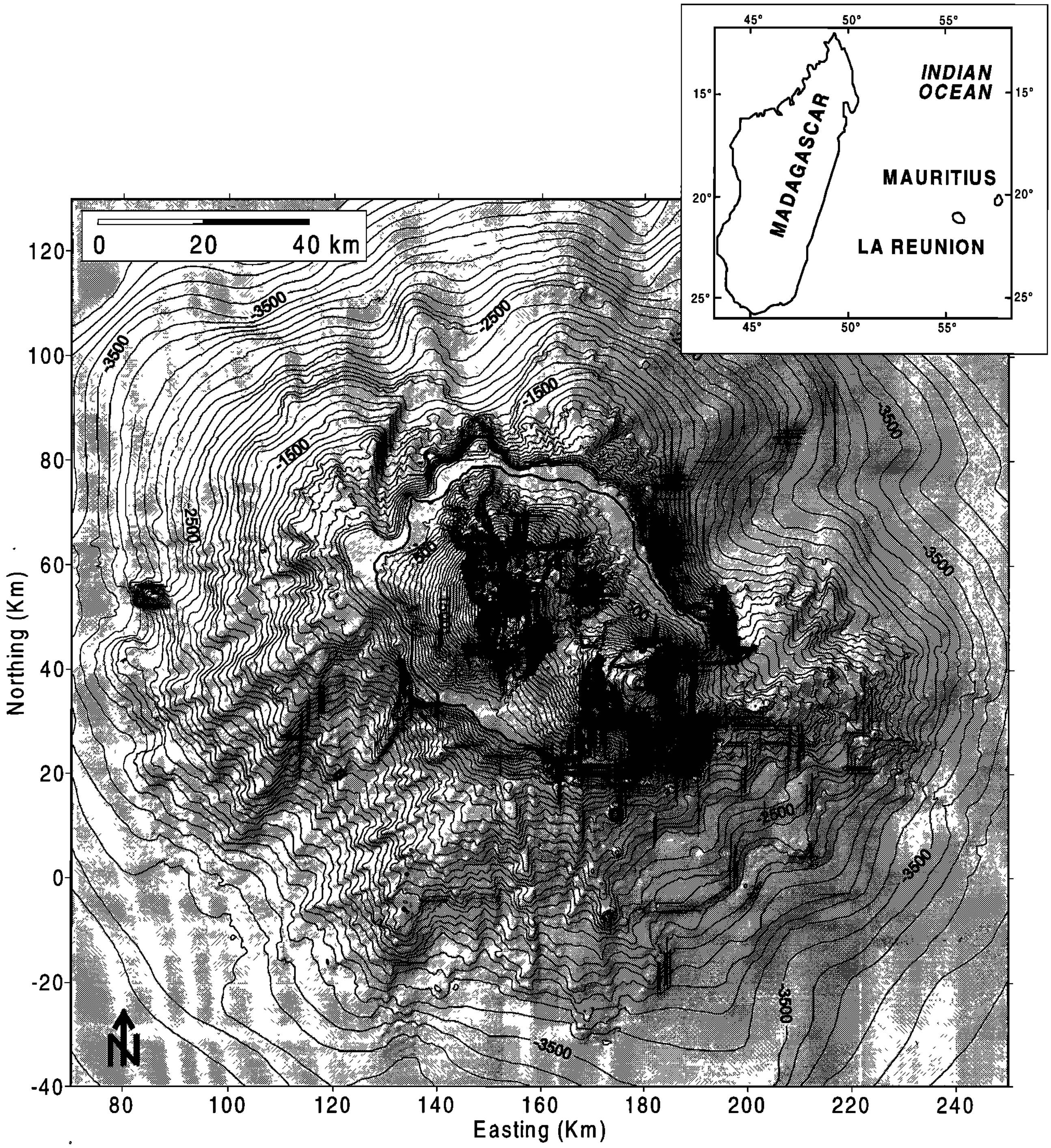

Figure 1. Map showing the topography of the island and surrounding sea floor (courtesy of Philippe Labazuy). Map grid based on Gauss-Laborde Réunion projection. Contour interval is 100 m. Accuracy of the map varies, with zones covered by detailed conventional or multibeam bathymetry showing greater detail. Inset is location of Réunion in the southwest Indian Ocean.

(Figure 1). Réunion volcanism may be associated with either the hot spot that generated the Deccan Trapps and a volcanic chain whose younger structures are Mauritius and Réunion islands [*Duncan et al.*, 1989] or, as proposed more recently by *Burke* [1996], to a younger hot spot.

The island of Réunion comprises only a fraction of a much larger volcanic system. Rising above a seafloor of Paleocene age, the Réunion edifice is a flattened cone having a basal diameter of 200 to 240 km and height of about 7000 m (Figure 1). Recent seismic studies [*Charvis et al.*, 1999; *Gallart et al.*, 1999; *de Voogd et al.*, 1999] have revealed remarkable structures in the interior of the edifice and underlying lithosphere. The most notable of these features are the virtual absence of crustal flexure beneath the island and the presence of an intermediate-velocity layer at the crust-mantle interface. This underplated body, 140 km wide and up to 3 km thick, is centered beneath the southwestern part of Réunion. Ages of the oldest surficial rocks are more than 2.08 Ma old [*McDougall*,

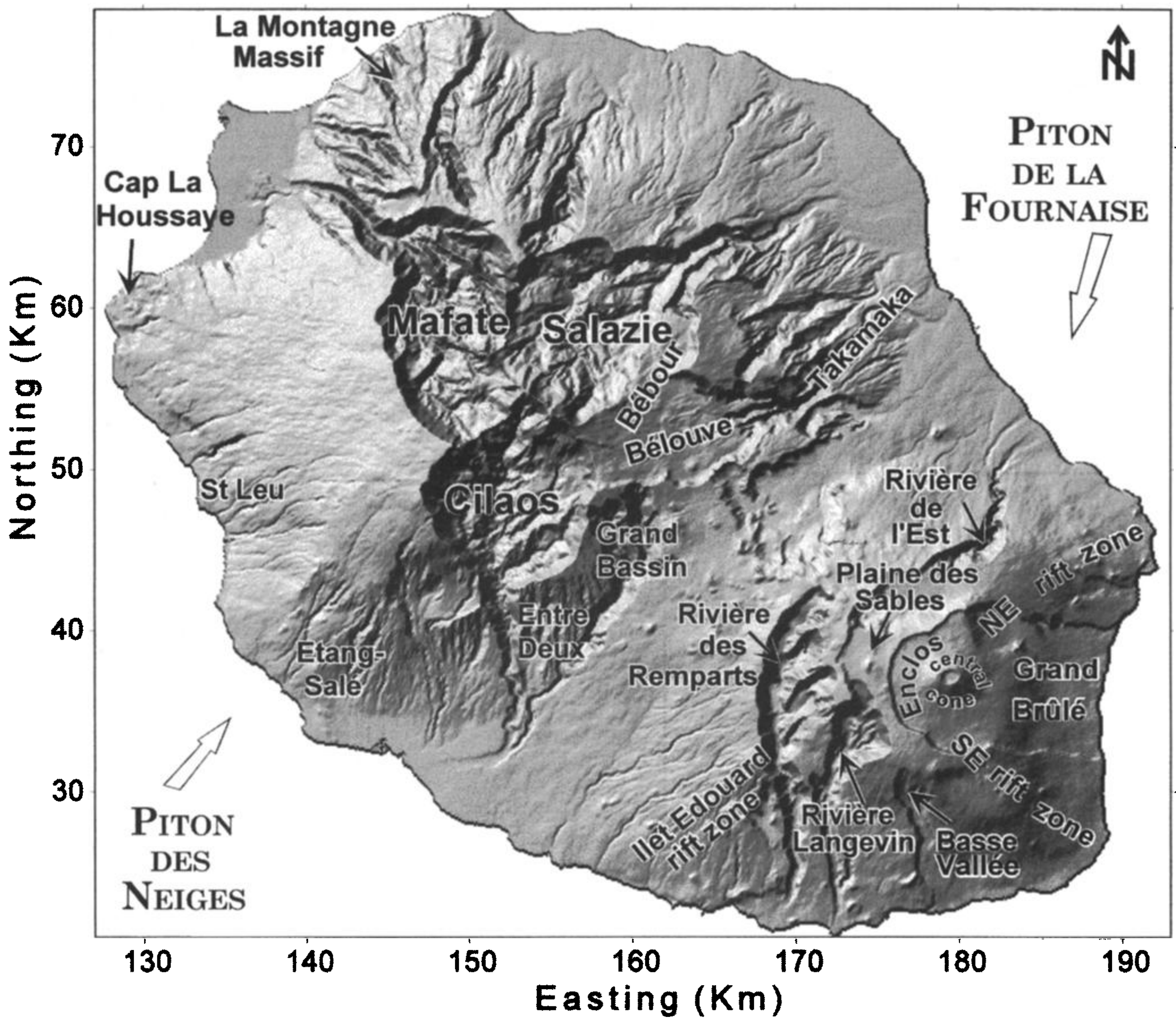

Figure 2. Shaded relief map of Réunion Island (illumination from the NW) with location of the main places discussed in text. Coordinates in kilometers (Gauss-Laborde Réunion projection).

1971], but because the subaerial part of Réunion comprises only 3% of the volcanic system [*de Voogd et al.*, 1999] (an estimate does not include the volume of the underplated material, estimated by *Charvis et al.* [1999] to be less than half that of the material emplaced above the plate), the present effusive rate of 0.34 m^3 s^{-1} [*Lénat and Bachèlery*, 1988] suggests that the growth of Réunion began ~ 7 Ma (the assumed rate is the rate of exogenous growth; it does not include endogenous growth or possible variations of magma production over the time). The island itself is composed of two volcanic massifs: Piton des Neiges and Piton de la Fournaise (Figures 2 and 3).

Piton des Neiges, which occupies the northwestern two thirds of the island, is a dormant volcano. Its oldest dated lava flows are 2.08 Ma basalts. Following a basaltic shield building stage, from before 2.08 Ma to after 0.423 Ma, Piton des Neiges erupted alkaline differentiated lavas between 330 and 12 ka [*McDougall*, 1971; *Gillot and Nativel*, 1982; *Deniel et al.*, 1992] (Figure 3). Although the structural evolution of Piton des Neiges has been the subject of several works [*Chevallier and Vatin-Perignon*, 1982; *Rançon*, 1982; *Rocher*, 1988; *Kieffer*, 1990a 1990b; *Kieffer et al.*, 1993; *Gillot et al.*, 1994; *Lecoîntre*, 1992], no clear general model has yet been established. One reason of this failure lies in the complexity of the geological pattern developed over more than 2 Myr. of volcanic, volcano-tectonic activity, and high rates of erosion. Another main reason was the lack of knowledge regarding both the submarine parts of the volcano and its interior. In recent years, new bathymetric, gravity, and seismic data have provided much additional information. The bathymetry (Figure 1) shows that the submarine flanks of Piton des Neiges are mostly composed of huge landslide deposits [*Lénat and Labazuy*, 1990]. This implies that Piton des Neiges has been repeatedly affected by landslides in different directions during its growth. The new gravity map of the island [*Malengreau et al.*, 1999] shows that the center of Piton des Neiges is underlain by a large, shallow, and deeply rooted (several kilometers) complex of intrusions, gabbros and cumulates. This indicates that the growth of Piton des Neiges began in the early stages of Réunion volcanism, with

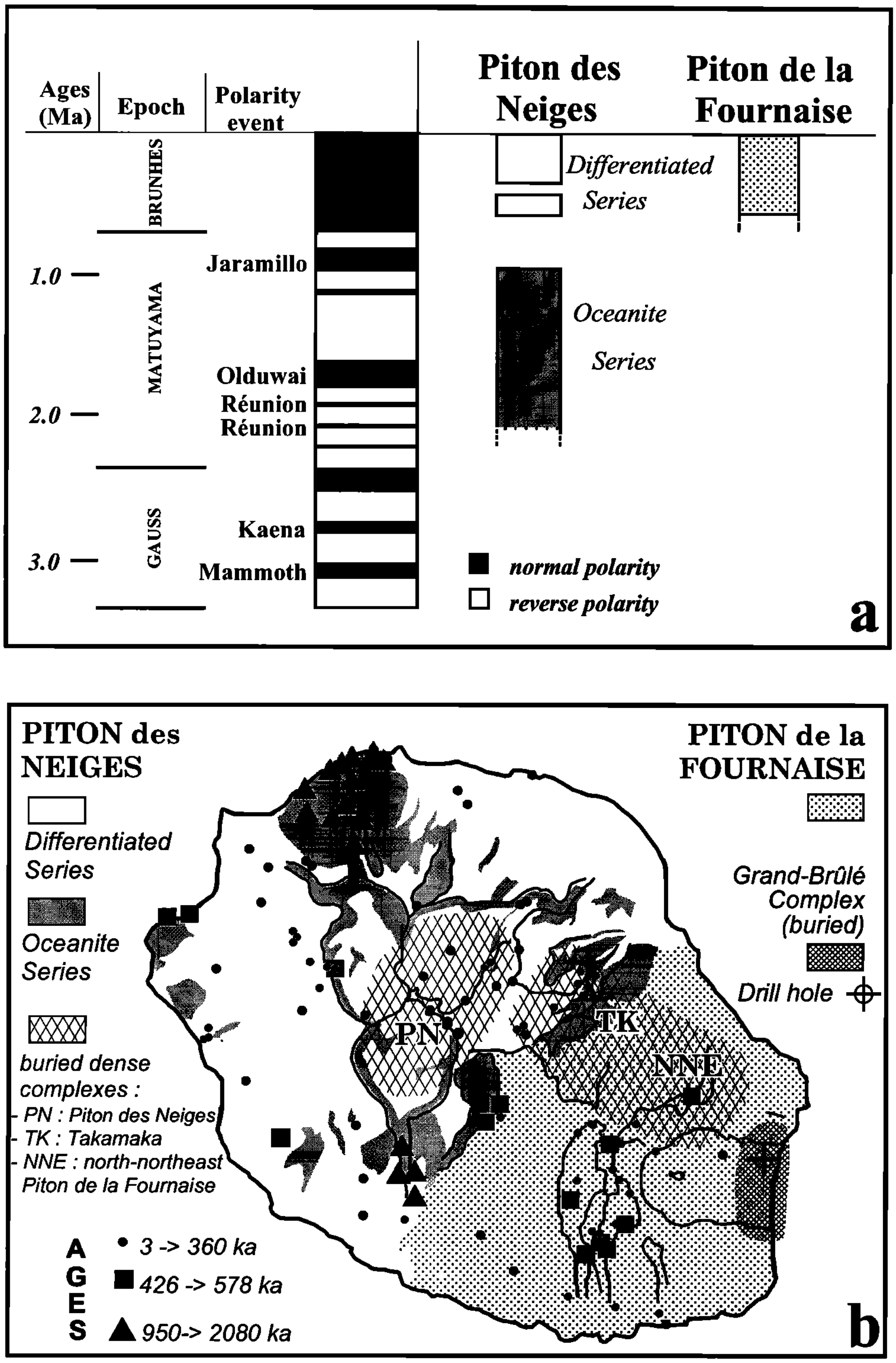

Figure 3. (a) Diagram showing time relations between geomagnetic epochs and the evolution of Piton de la Fournaise and Piton des Neiges. Because of the preponderance of the thermoremanent component in the natural magnetization of the volcanic rocks, the rocks erupted during the Brunhes Epoch should have a bulk normal magnetization, whereas the rocks older than the Brunhes-Matuyama reversal should have a bulk reverse magnetization. (b) Geological sketch map and geochronological data. For Piton des Neiges, only the Oceanites and the Differentiated Series are distinguished. Also shown is the extent of the dense hypovolcanic complexes. The available radiometric dates are clustered in three groups: 3 to 360 ka, a period that encompasses the Differentiated Series of Piton des Neiges volcano; 426 to 578 ka, a period that encompasses the Oceanites of Piton des Neiges emplaced during the Brunhes normal-polarity epoch; and 950 to 2080 ka, the Oceanites of Piton des Neiges erupted during the Matuyama reverse-polarity epoch. (No rock ages from Piton des Neiges have been found between 360 and 426 ka, 578 and 950 ka, or before 2080 ka.)

the complex of dense rocks developing upward as the volcano grew [*Ryan*, 1987]. *Malengreau et al.* [1999] also suggest that a secondary gravity high, centered on the east-northeast flank of Piton des Neiges, may be associated with an old, buried volcano (Takamaka) which is recognized also in seismic data [*Gallart et al.*, 1999].

Piton de la Fournaise, at the southeastern part of the island (Figures 2 and 3) is a highly active basaltic shield volcano. Most of its known activity has been restricted to effusions from its central cone and northeast and southeast rift zones. Owing to the presence of deep valleys, more than half a million years of the history of Piton de la Fournaise can be inferred from surficial evidence [*Gillot and Nativel*, 1989]. The oldest lava flows (0.527 to 0.498 Ma) crop out at the bottoms of Remparts, Langevin, and Est valleys (Figures 2 and 3). Although the structural evolution of this shield volcano appears simpler than the longer, complicated evolution of Piton des Neiges, its study has yielded contrasting and somewhat contradictory hypotheses. A series of caldera-like rims and curved rims of valleys have been interpreted by some workers as the headwalls of successively smaller eastward moving landslides [*Duffield et al.*, 1982; *Gillot et al.*, 1994] and by other workers as parts of actual caldera rims [*Chevallier and Bachèlery*, 1981; *Bachèlery and Mairine*, 1990; *Bachèlery*, 1995]. All of these authors, however, agree that the Grand-Brûlé depression is the scar of an eastward moving landslide.

Marine investigations offshore of Piton de la Fournaise have provided additional constraints to the structural model of the volcano [*Lénat et al.*, 1989, 1990; *Rousset et al.*, 1987, 1989; *Labazuy*, 1991, 1996]. About 600 km^3 of landslide material have been recognized on the submarine eastern flank of the island. This material is composed almost entirely of fragmented, subaerially erupted lava flows whose ages range between a few thousand years and 100 ka. These ages were obtained on samples dredged from the surfaces of the landslides, and therefore this does not preclude a larger range of ages in deeper parts of the deposits. This volume is about 10 times larger than the present topographic scar of the Grand-Brûlé slide and would represent the equivalent of about 50,000 years of magma production from Piton de la Fournaise, assuming the historical effusion rate [*Lénat and Bachèlery*, 1988]. These results led *Lénat et al.* [1990] and *Labazuy* [1996] to propose that (1) eastward directed landslides have recurred during at least the last 100 kyr (2) the Enclos depression could be the headwall of the Grand-Brûlé slide instead of a caldera, and (3) the Plaine des Sables depression could be an earlier analog of the Enclos (i.e., a slide headwall and not a caldera). However, in contrast to the hypothesis by *Duffield et al.* [1982] and *Gillot et al.* [1994], these eastward directed landslides would have occurred inside a relatively narrow (10-13 km) corridor, instead of along curved faults cutting the entire massif. The narrowness of the inferred corridor is supported by the distribution of landslide deposits on the submarine flank [*Labazuy*, 1996, Figures 1 and 3] and by the presence of constructional features in the continuation of the subaerial NE and SE rift zones (these apparently old features will be discussed later in the paper).

The discovery, by drilling (Figure 3b), of a large intrusive and cumulate complex 1000 m beneath the Grand-Brûlé area [*Rançon et al.*, 1989] has added complexity to the volcanological story. This extensive (Figure 3b), deeply rooted (5-6 km according to gravity models [*Rousset et al.*, 1989; *Malengreau et al.*, 1999]) complex has not been identified with any known volcanic structure, and it has therefore been regarded as an ancient volcanic center predating Piton de la Fournaise [*Rançon et al.*, 1989]. As in the case of Piton des Neiges, the fact that the dense complex is deeply rooted indicates that this volcanic center started to develop in the early stages of Réunion volcanism. An alternative interpretation would be to consider that the Grand-Brûlé complex represents an early stage in growth of Piton de la Fournaise itself, having been displaced laterally in a large proximal slump block of a landslide having a deep slip surface. Although this hypothesis cannot be categorically rejected, the fact that gravity models show that the complex extends vertically down to, at least, the underlying crust and that the seismic data do not reveal the presence of landslides at the crust-edifice interface in this area [*de Voogd et al.*, 1999] strongly suggest that the complex is not displaced. Thus this eastern volcano, which we named Alizés volcano, and Piton des Neiges appear to comprise the two primary and long-lasting volcanic foci of Réunion. *Malengreau* [1995] and *Malengreau et al.* [1999] also observe a gravity high beneath the northern flank of Piton de la Fournaise and suggest that it could be associated with another separate ancient volcano or a continuation of Takamaka volcano. By contrast, Piton de la Fournaise, with virtually no underlying dense complex, appears as a young manifestation of Réunion volcanism. In detail, however, secondary gravity highs suggest the presence of a small complex of intrusions and cumulates beneath its old center (west of the present center) and of dense rocks beneath part of its southern flank.

3. Data Acquisition and Processing

The magnetic data used here come from three sources: an aeromagnetic survey, two detailed shipborne surveys, and individual routes from oceanic cruises (Plate 1a).

3.1. Aeromagnetic Survey

An aeromagnetic survey of Réunion was flown at a constant altitude of 3500 m above sea level (asl) [*Galdéano et al.*, 1988] along south-north lines spaced 3 km apart with west-east tie-lines spaced 10 km apart. Over the central zone of Piton de la Fournaise, the flight line and tie line spacings were changed to 1 and 3 km, respectively. Along the profiles the distance between successive measurements is about 150 m. The survey extended 10 to 30 km beyond the coast of the island. Owing to technical problems during the survey, large departures from the planned flight pattern occurred, but the intended coverage was nevertheless achieved.

3.2. Sea Level Surveys

The eastern and southwestern submarine flanks of Réunion are covered by two detailed surveys [Lénat et al., 1990; Stoffers and SO87 Cruise Party, 1994] (Plate 1a) which allow detailed mapping of these areas. In the other areas we used generally isolated profiles, mostly from oceanic cruise routes to and from La Réunion and Mauritius. Although the latter generally provided only a low density of data coverage, they proved useful for defining the regional magnetic trends outside the boundaries of the aeromagnetic and detailed marine surveys [*Malengreau*, 1995]. The marine data also allowed us to construct the magnetic map that we used to describe the geodynamic context of Réunion (Plate 1b). All magnetic data were reduced to anomaly values using the appropriate definitive geomagnetic reference field model.

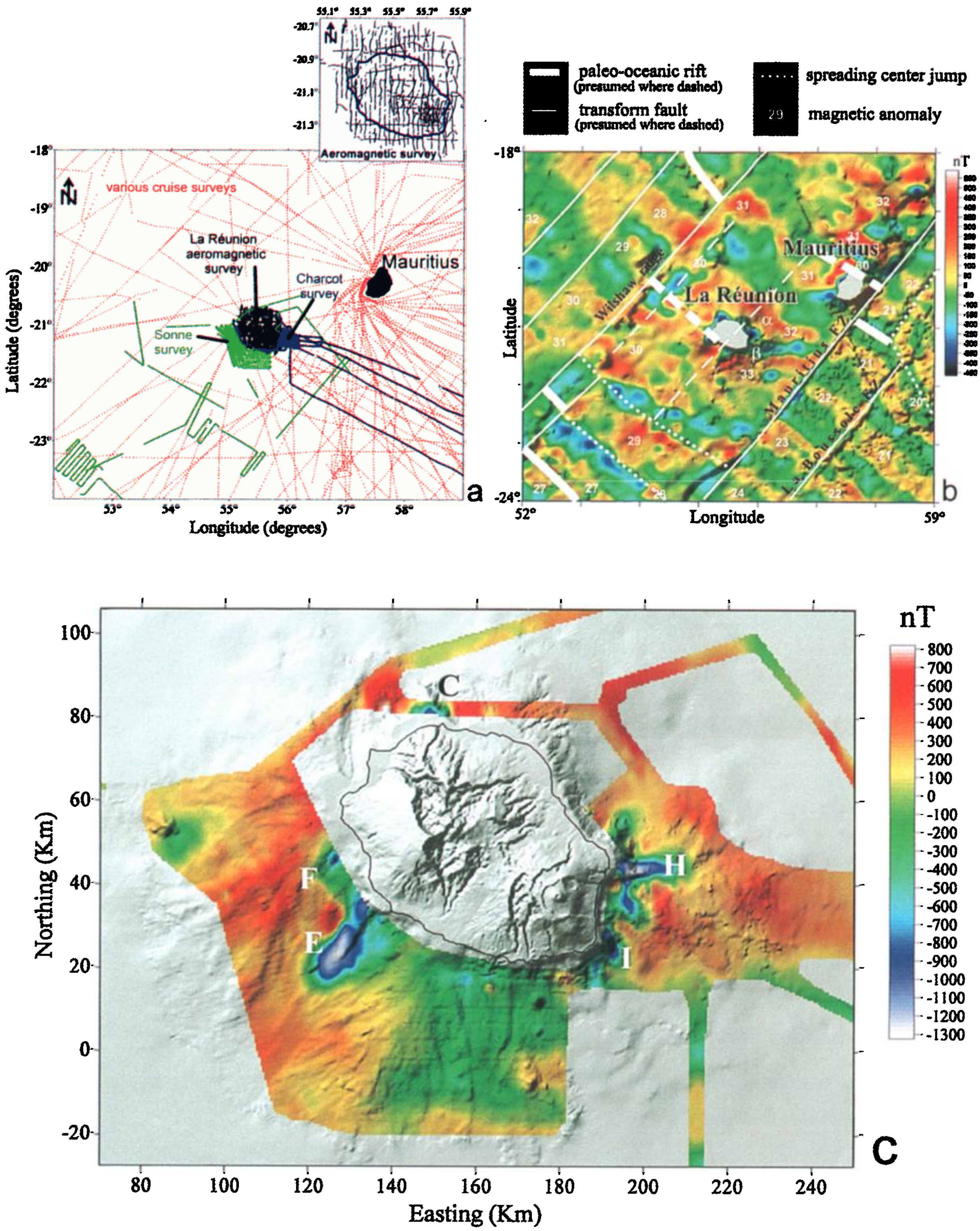

Plate 1. (a) Locations of the magnetic data used in this study. (b) Regional magnetic anomaly map, based on the shipboard data of Plate 1a superimposed on shaded bathymetry. The superimposed oceanic features (rifts, fractures, and anomaly numbers) are from Dyment [1991]. (c) Reduced to pole magnetic anomaly map computed at sea level from Sonne and Charcot surveys (see Plate 1a), superimposed on shaded bathymetry. Map coordinates in kilometers (Gauss-Laborde Reunion project). (d) Reduced to pole magnetic anomaly map computed at 3500 m asl superimposed on shaded topography. The map is obtained by merging the sea-level (upwardly continued) and aeromagnetic data. Letters refer to anomalies discussed in the text. (e) Reduced to pole magnetic anomaly map computed at 7500 m asl superimposed on shaded topography. This map is obtained by upward continuation of Plate 1d. Letters refer to anomalies discussed in the text. The two straight lines show the location of profiles of Figure 7.

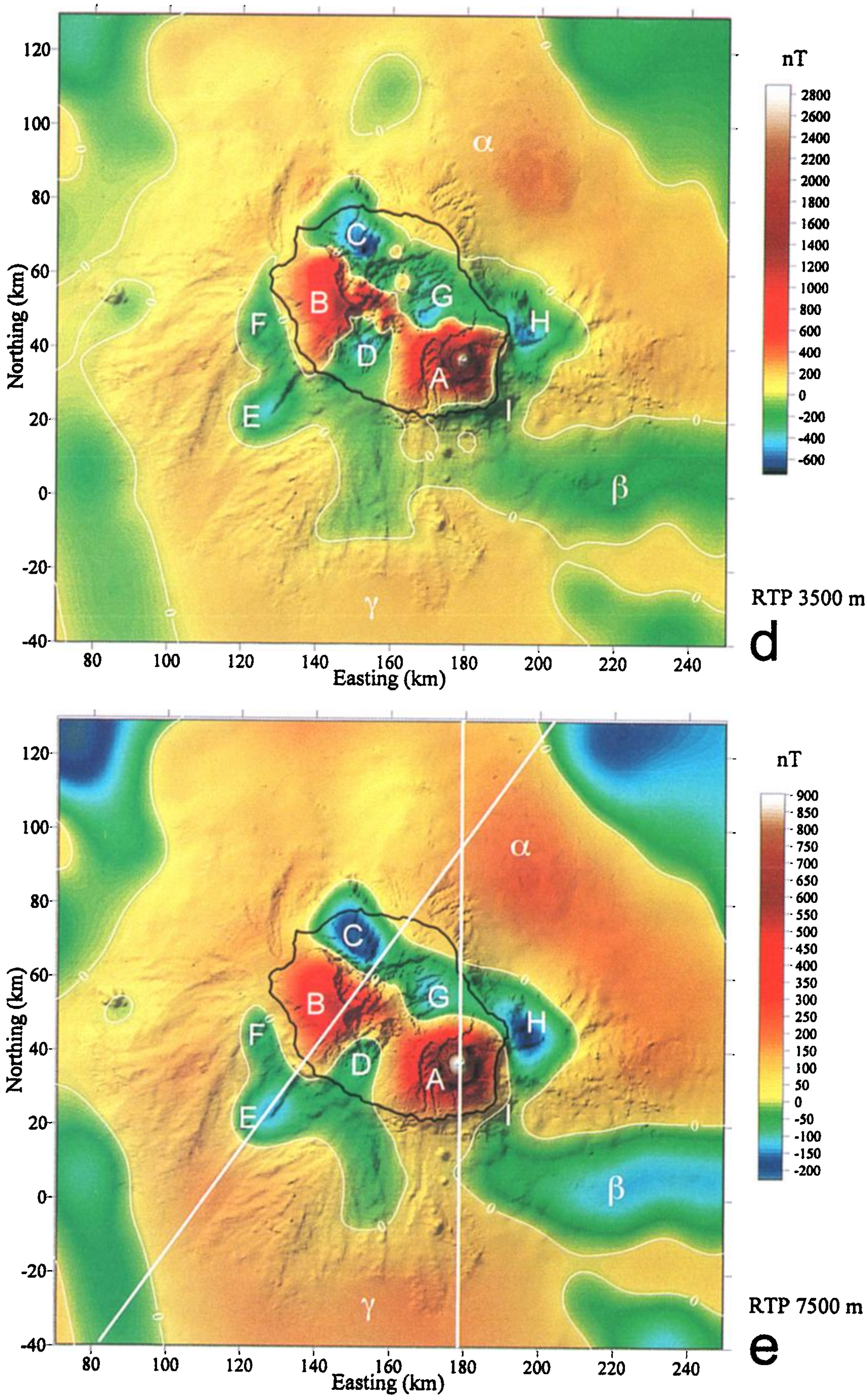

Plate 1. Continued

3.3. Reduction to Pole (RTP) and Upward Continuation of Anomaly Maps

At Réunion's latitude, because of the inclination of the magnetic field, the anomaly induced by a normally or reversely magnetized body will have a strong dipolar appearance. A normally magnetized body will give rise to a magnetic high to the north, with a maximum located near its northern edge and a magnetic low to the south with a minimum located near its southern edge. The location of the sources of the magnetic anomalies are thus difficult to visualize, contrary to the case of gravity where the anomalies are monopolar and always occur above the causative bodies. To reduce the complexity of the magnetic anomaly pattern, the data were reduced to pole (RTP) [*Baranov*, 1957]. This transformation cancels, or significantly reduces, the dipolar appearance of the anomalies and offsets them to their sources. A correct RTP transformation requires the directions of both the Earth's magnetic field and of the total magnetization of the rocks to be known. At Réunion the magnetic field has a declination of -18° and an inclination of -57°. These values are significantly different from those of a geocentric axial dipole field (declination of 0° and inclination of -36°) which is assumed to represent an average field direction over long periods of time. The direction of the total magnetization was assumed to be that of a geocentric axial dipole field because a high Koenigsberger ratio (the ratio of the remanent magnetization over the induced magnetization) is usually characteristic of volcanic rocks (see Table 1).

The amplitude and wavelength of the magnetic anomaly caused by a given magnetic body depend upon the distance between the measurement and the body. The amplitude decreases nonlinearly with the distance (for a magnetic dipole, the amplitude is a function of $1/d^3$, where d is the distance to the dipole). Anomalies from a survey close to the ground surface express mainly topographic relief and small-scale shallow sources. On the other hand, a higher altitude survey will enhance deeper and larger sources. A transformation called upward continuation allows computation of anomaly maps at altitudes higher than that of observation [*Henderson and Zietz*, 1949]. We used this transformation to merge the marine and aeromagnetic surveys and to compute an anomaly map at 7500 m asl. RTP and upward continuations were performed using the program FFTFIL from *Hildenbrand* [1983], available as part of the U.S. Geological Survey Potential-Field Geophysical Software Package [*Cordell et al.*, 1992].

Table 1. Magnetic Properties of Some Volcanic Rocks From Réunion

Age, Ma	n	NRM, A m^{-1}	χ, 10^{-2} SI	Q	Reference
		Piton de la Fournaise[a]			
0.0047 to 0.011	13	8.07	1.75	16.2	*Chauvin et al.* [1991]
0.052	11	5.63	1.44	13.7	A. Chauvin (personal communication, 1994)
0.06	7	13.08	1.88	24.5	A. Chauvin (personal communication, 1994)
0.082 to 0.18	17	5.21	2.16	8.5	*Chauvin et al.* [1991]
0.082 to 0.18	13	3.95	1.86	7.5	A. Chauvin (personal communication, 1994)
0.25 to 0.5	27	6.45	2.99	7.6	A. Chauvin (personal communication, 1994)
		Piton des Neiges and Piton de la Fournaise[b]			
0 to 2.2	>100	3.6	0.25	5.7	Chamalaun [1968]

[a]Abbreviations are n, number of samples considered; NMR, natural remanent magnetization intensity; χ, magnetic susceptibility; Q, Koenigsberger ratio.

[b]Mean NRM and χ value given by *Chamalaun* [1968] for samples from Piton des Neiges and Piton de la Fournaise.

3.4. Magnetic Anomaly Maps Constructed for Réunion

We have computed a regional anomaly map at sea level to describe the geodynamic framework of Réunion (Plate 1b) and a more detailed RTP anomaly map, also at sea level, in the areas covered by the dense Charcot and Sonne surveys (Plate 1c). The sea level data were then upward continued to the altitude of the aeromagnetic survey (3500 m asl) and merged with the aeromagnetic data (using the program JMRG from *Cordell et al.* [1992]). The resulting anomaly map was reduced to pole to obtain the map of Plate 1d. Finally, we computed a map at the altitude of 7500 m asl (Plate 1e) from which we extracted the two profiles interpreted in Figure 7. The reason for computing an anomaly map at 7500 m was to reduce the topographic effects and enhance deeper magnetic structures of the island.

4. Magnetic Interpretation

4.1. Magnetic Properties of Volcanic Rocks

Magnetization contrasts between rock masses at Réunion can arise from two different causes: differences in magnetization direction or differences in magnetization intensity. The apparent magnetization is the vector sum of the induced magnetization (M_i) and of the natural remanent magnetization (NRM). M_i is the product of the magnetic susceptibility (k) and the local Earth's magnetic induction field (B_E). NRM is the vector sum of several types of remanent magnetization. In the case of volcanic rocks, thermoremanent magnetization (TRM) is usually by far the most important component. This magnetization is acquired as rocks cool below Curie temperature and it usually has a large intensity and a high stability over time unless chemically altered. TRM also has the direction of the ambient B_E at the time of the cooling of the lava. Another type of remanent magnetization that can have some importance at the scale of our work is viscous remanent magnetization (VRM). VRM is produced by long exposure to an external field, is oriented with the ambient B_E, and its buildup is a logarithmic function of time. VRM can represent one fifth of the NRM in volcanic rocks [*Prévot*, 1975]. Table 1 shows average values of NRM and k determined at different sites by several workers. The Koenigsberger ratios (NRM/M_i) for volcanic rocks show the typical dominance of NRM over induced magnetization.

At the scale of the interpretation of the magnetic structure of Réunion, we consider large volumes of rocks instead of individual lava flows. Thus, like in paleomagnetism, we shall assume that the average direction of the TRM for a sequence of rocks spanning tens to hundreds of thousands of years is that of a geocentric axial dipole (declination = 0°, inclination = -36° for normally magnetized rocks, and + 36° for reversely magnetized rocks) and not that of the present-day Earth's magnetic field (declination = -18°, inclination = -57°). Conversely, the VRM and the M_t will be oriented in the direction of the present field. Note that for the same value of TRM a normally magnetized rock will have a larger apparent magnetization than a reversely magnetized rock.

The magnitudes of NRM and k depend not only upon the amount and nature of titanomagnetite content of the rock but also on its grain size, composition, and thermal history (see a discussion by *Hildenbrand et al.* [1993]). Generally speaking, basalts will show higher values than will differentiated lavas. Two other main factors may act on the magnetization in volcanic contexts: hydrothermal alteration and temperature. Hydrothermal alteration will alter the highly magnetic titanomagnetite to nonmagnetic or poorly magnetic minerals. High temperatures will also tend to decrease TRM as they approach Curie temperature. Thus the volume encompassing a magma reservoir may have a very weak TRM.

4.2. General Trends in Magnetization Directions of the Volcanic Rocks of Réunion

The range of ages of the dated rocks of Piton des Neiges spans the Brunhes and Matuyama paleomagnetic epochs, whereas the oldest observable rocks of Piton de la Fournaise still belong to the Brunhes epoch (Figure 3a). On a general level we can infer from the geomagnetic timescale that the lava piles younger than the Brunhes-Matuyama reversal (0.78 Ma [*Spell and McDougall*, 1992; *Izett and Obradovich*, 1994; *Bassinot et al.*, 1994]) should have a normal magnetization, whereas older formations will have a bulk reversed magnetization, because the periods of reversed geomagnetic field were dominant during the Matuyama.

4.3. Qualitative Interpretation of the Anomalies of Réunion

The anomaly map (Plates 1d and 1e) is dominated by the presence of two main positive anomalies: one over Piton de la Fournaise and one over the western flank of Piton des Neiges. Anomaly A, over Piton de la Fournaise, is a feature that was expected, but the actual shape of the anomaly presents noteworthy features. Its extent is narrower than that of Piton de la Fournaise formations at the surface (Figure 3b). This can be observed on its northern flank. In addition, the anomaly does not extend offshore. The maximum of the anomaly coincides with the central area of the volcano. This can be related to the effect of the relief as well as to a greater thickness of the normally magnetized products here and/or to higher values of magnetization.

The anomaly pattern over Piton des Neiges is more surprising. From the available ages (Figures 3a and 3b) it is known that rocks older than the Brunhes-Matuyama reversal are present in a few places: La Montagne massif, valleys northeast of Belouve and Bebour depressions and south of Cilaos Cirque. Apart from these localized zones the whole surface of the massif is covered by rocks younger than 0.78 Ma. The fact that a main positive zone (B on Plates 1d and 1e) is restricted to the western flank and summit area suggests that in other areas the products emitted during the Brunhes epoch represent only a relatively thin coating over larger volumes of older rocks.

In addition to the two main positive anomalies of the island, we note six negative anomalies (Plates 1b and 1e) and zones having no, or weak, magnetic signature. Anomaly C, associated with La Montagne massif can be interpreted straightforwardly as having mostly reverse magnetization, owing to the ages of its rocks (Figure 3b). Negative anomaly D also coincides with surficial rocks older than 0.78 Ma (Figure 3b) but extends over a broader area, eastward overlapping slightly the southwest flank of Piton de la Fournaise, suggesting a relatively small thickness of the < 0.78 Ma formations from Piton de la Fournaise and Piton des Neiges. Offshore, anomalies E and F form a large negative zone coalescent with anomaly D.

Negative anomaly G coincides with outcrops of > 0.78 Ma rocks at the northeast of Belouve and Bebour depressions but extends over a larger area, merging to the northwest with anomaly C and to the southeast with negative anomaly H along the north and northeast flanks of Piton de la Fournaise. Anomalies H and I to the northeast, east and southeast of Piton de la Fournaise, are partly coincident with bathymetric highs extending from Piton de la Fournaise rift zones.

A final qualitative observation is the general weakness or absence of magnetic features on the submarine flanks, except for anomalies C, E, F, H, and I. This suggests that most of the flanks either have a homogeneous magnetization or, more likely, are poorly magnetized. The latter interpretation would be consistent with flanks composed mostly of landslide debris which may have accumulated repeatedly throughout the building of Réunion, as suggested by *Holcomb* [1990], *Holcomb and Searle* [1991], and *Moore et al.* [1994] for other the oceanic islands. Longer wavelength anomalies α, β, and γ of the distal submarine flanks probably originate principally from the oceanic crust beneath Réunion (see the regional magnetic map on Plate 1b) and therefore will not be considered here.

4.4. Evidence of Reversely Magnetized Formations at the Base of Réunion Volcanic Massifs

On the sea level map (Plate 1c), intense negative anomalies are observed at several places near the seashore. As demonstrated below, their intensity implies that they are created by reversely magnetized rocks. The sea level data were thus instrumental in establishing the presence of large volumes of rocks older than 0.78 Ma at the base of Piton de la Fournaise and Piton des Neiges.

4.4.1. Eastern zone of the island (Figure 4). Anomalies H1 and I coincide partly with bathymetric highs offshore beneath the present-day NE and SW rift zones of Piton de la Fournaise (Figure 1). The analysis of those bathymetric highs led *Labazuy* [1991] and *Lénat et al.* [1989, 1990] to infer that they are remnants from old volcanic constructions, unrelated to the growth of the recent (< 0.5 Ma) Piton de la Fournaise.

The signatures of the negative anomalies differ strikingly from those of positive ones in this area. The negative anomalies are spatially well defined and have high amplitudes. Two two-dimensional (2-D) models along two lines (located on Figure 4a) are shown on Figures 4b and 4c. Those models, as well as the other models computed for sea level data, have been made as simple as possible, having simple shapes, with only one magnetization contrast considered. Deriving more complex models would be meaningless in the absence of supplementary constraints. Therefore these simple 2-D models should not be considered as accurate models of the internal structure but only as models establishing the presence of major magnetization contrasts within the upper submarine flanks of Réunion. The models show that high negative magnetization contrasts are required to account for the amplitudes of the negative anomalies. This implies that the anomalies arise from reversely

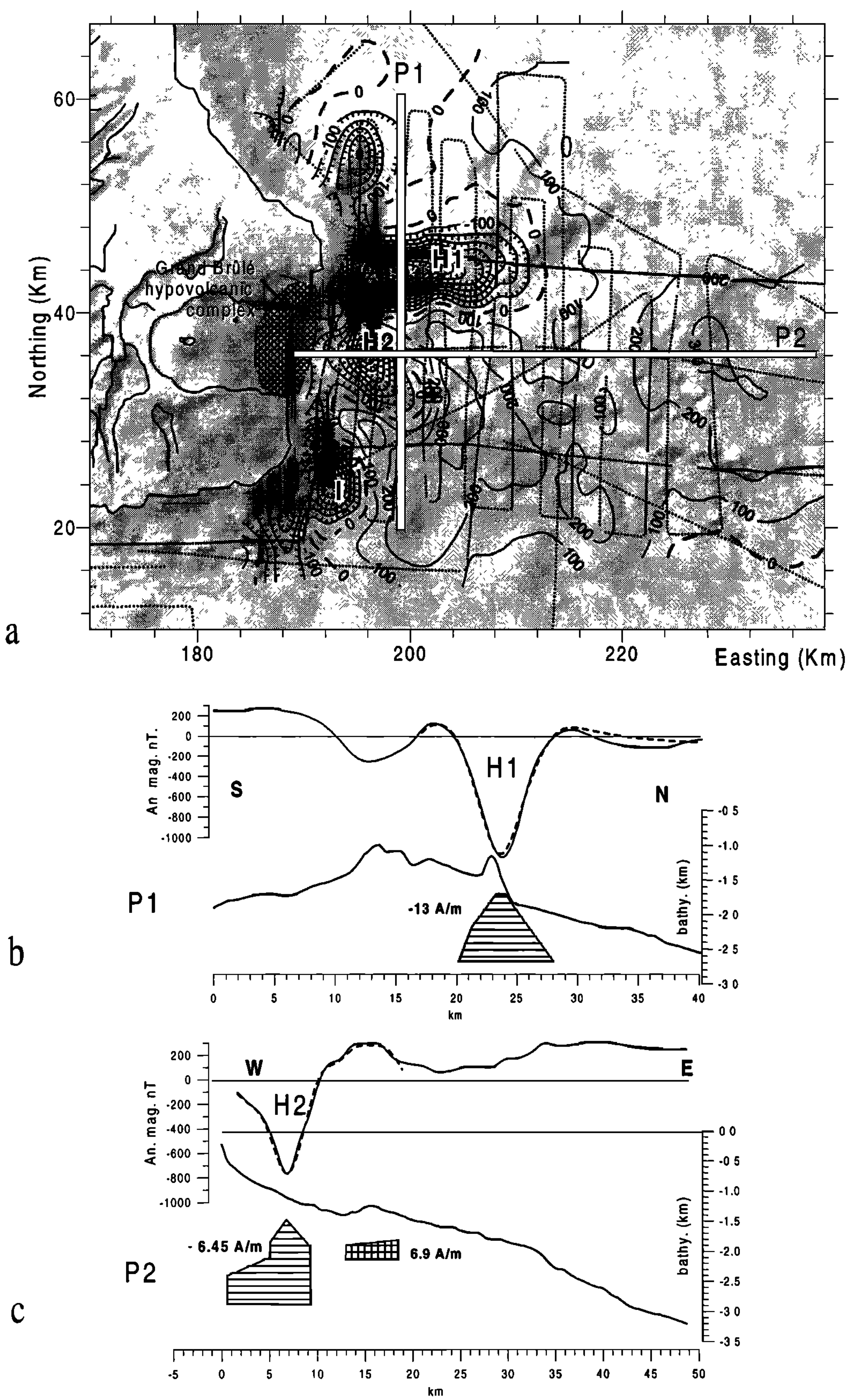

Figure 4. Interpretation of the RTP sea level magnetic anomalies near the eastern seashore. (a) Anomaly map superimposed on shaded bathymetry. H1, H2 and I are anomalies discussed in the text. P1 and P2 are lines of profiles for Figures 4b and 4c. Magnetic contours are 100 nT. Black dots show location of the magnetic measurements along the ship track. (b) Bathymetric and magnetic profiles of anomaly H1 along line P1; dashed line, 2-D model profile. (c) Bathymetric and magnetic profiles of anomaly H2 along line P2; dashed line, 2-D model profile.

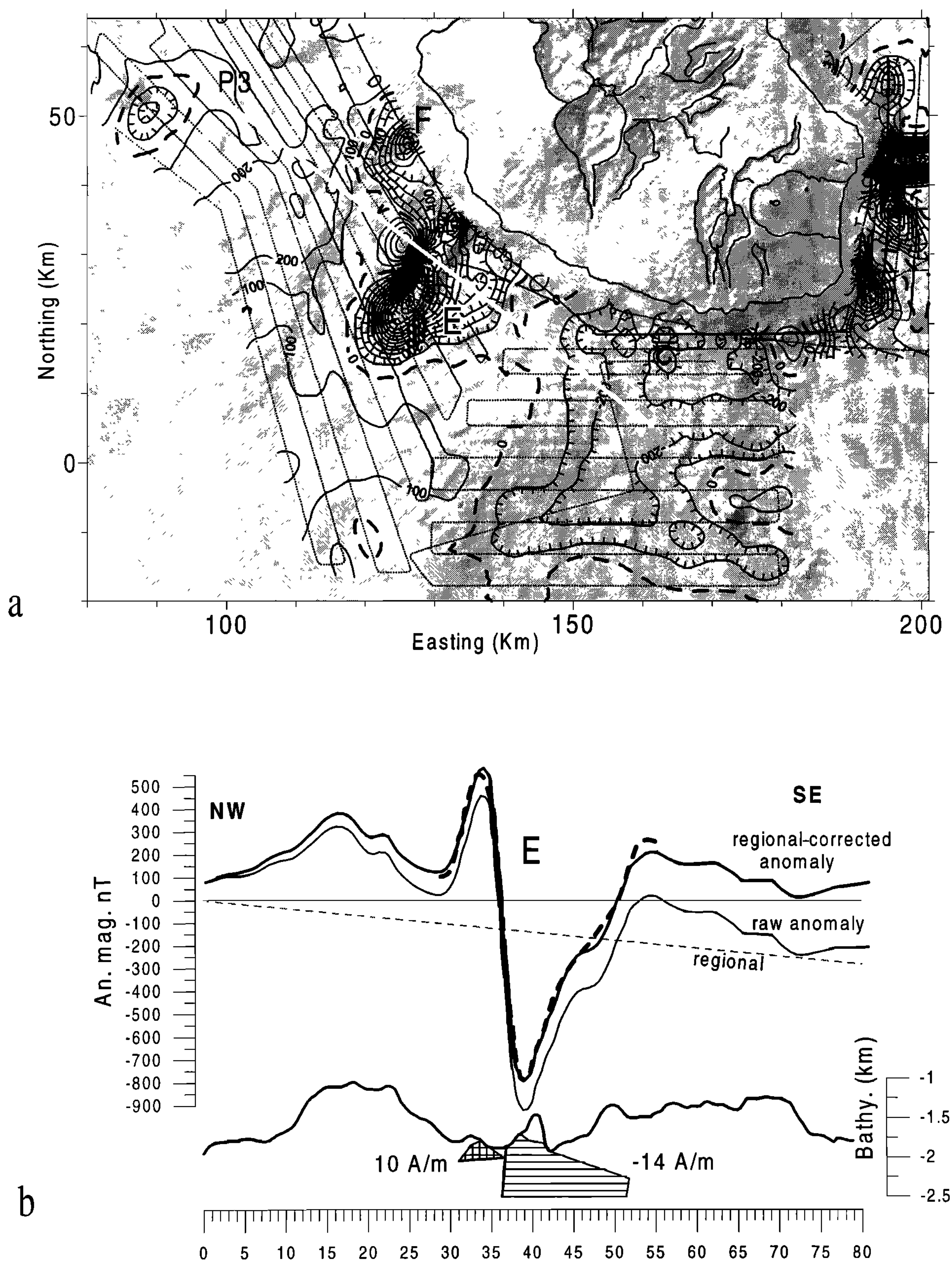

Figure 5. Interpretation of the RTP sea level magnetic anomaly near the southwestern seashore. (a) Anomaly map superimposed on shaded bathymetry. E and F are anomalies discussed in the text. P3 is the line of profile for Figure 5b. Magnetic contours are 100 nT. Black dots show location of the magnetic measurements along the ship track. (b) Bathymetric and magnetic profiles of anomaly E along line P3; dashed line, 2-D model profile.

magnetized bodies rather than by contrasts between normally magnetized formations. This is further supported by the fact that the eastern submarine flank is mostly formed by disorganized products from slides [*Lénat et al.*, 1989, 1990; *Labazuy*, 1996; *de Voogd et al.*, 1999]. These landslide formations probably have no bulk TRM magnetization, because the blocks are randomly rotated, and therefore cannot produce negative contrasts as high as required by the models.

The modeling of anomaly H1 (Figure 4b) shows that it cannot be explained by the topographic effect of the sharp topographic ridge which nearly coincides with the minimum of H1 on the profile. A broader, and presumably deeper, structure must be considered to explain the anomaly. The interpretation of anomaly H2 (Figure 4c) requires a vertical discontinuity (or variation of magnetization) at about 5 km from the coast, about where the eastern boundary of the Grand-Brûlé dense complex is inferred from gravity data [*Rousset et al.*, 1989]. The existence of the normally magnetized structure (6.9 A m^{-1}), added to the model in order to improve the fit between the observed and computed curves, is highly questionable, because the general level of about 200 nT to the east of H2 is probably related to the long-wavelength positive anomaly visible on Plates 1d and 1e.

4.4.2. Southwestern zone of the island (Figure 5). Two minima (E and F) indicate a negative zone offshore of the southwest coast of the island. Anomaly E is conspicuously elongate toward the south-southwest and partly coincides with a nearshore submarine promontory (Figure 1) that continues farther offshore as a prominent submarine ridge. A 2-D model, along a line roughly perpendicular to the elongation of E, is shown on Figure 5b. The result is similar to what was observed in the interpretation of anomaly H1 (Figure 4b): (1) anomaly E does not correspond to a topographic effect of the ridge, but to a broader structure, and (2) the magnetization contrast required to account for the amplitude of the anomaly is large and should be associated with a reversely magnetized body, for the same reasons as for anomaly H1. The small, normally magnetized structure (10 A m^{-1}) models a short-wavelength, local anomaly visible on the maps on Figures 5a and Plate 1c. The southwestern negative zone is therefore similar to the one at the east of the island and suggests that reversely magnetized formations are present beneath the younger formations of Piton des Neiges in this area. The elongation of anomaly E suggests a rift zone-like structure.

4.4.3. Northern zone of the island (Figure 6). This area is an offshore continuation of the La Montagne massif, which constitutes the largest subaerial outcrop of rocks older than the Brunhes-Matuyama reversal. La Montagne massif is a pile of lava flows intersected by a high concentration of dikes that trend N20°W and have been interpreted as an old rift zone [*Chevallier and Vatin-Pérignon*, 1982]. Offshore, a submarine promontory and ridges (Figures 1 and 6a) mark the continuation of the La Montagne massif.

This area is incompletely covered by the marine magnetic surveys (Figure 6a). A 2-D model is presented on Figure 6b. The source of the anomaly seems wider than the ridge directly beneath the magnetic profile. The reason of this apparent inconsistency of the model arises from the limitation of the method used (2-D model and no variation of magnetization considered). In particular, because the topography deepens dramatically to the north in this area (as shown by the comparison of the topographic profiles T1 and T2) and the source is shallow, the 2-D approach is clearly not adapted. However, this simple model is sufficient to show that the interpretation of the anomaly requires a large negative contrast in magnetization, although lower than in the previous cases of the east and southeast zones of the island. The important point here is that the anomaly can be confidently related to subaerial formations having ages compatible with a reversed magnetization. On the aeromagnetic map (Plate 1d), the subaerial La Montagne massif corresponds to a negative anomaly that continues offshore, in agreement with sea level observations. In summary, the combined observations provide robust evidence that the negative anomalies observed offshore the east, southwest, and north coast of the island are caused by volcanic formations having reversed magnetization. These observations also strengthen the interpretation of the on-land negative anomalies D and G as caused by large volumes of reversely magnetized rocks.

4.5. Magnetic Interpretation Along Two Profiles Across the Island

The well-established interpretation of negative anomalies C to I as caused by large volumes of reversely magnetized rocks allows us to derive a more general model of the magnetic structure of the island. A 3-D modeling probably would be unrealistic considering the poor knowledge of the magnetizations at depth. We calculated instead simple 2.5-D models to establish and refine the coherence of the qualitative interpretation and of the sea-level models. Two characteristic profiles were selected (Plate 1e): one across Piton des Neiges and one across Piton de la Fournaise. In order to minimize the topographic effects, a uniform 3-D model of the island was first calculated using the program PFMAG3D from *Blakely* [1981]. The top of this overall model is defined by the topography and the bottom is a deep horizontal surface. Using this overall model, a simple topographic anomaly was calculated first, using a constant total magnetization having the moderate value of 1.5 A m^{-1}. The effects of the 2.5-D structures were then superimposed on this simple topographic anomaly. The 2.5-D models were calculated using the program SAKI [*Webring*, 1985].

4.5.1. Piton de la Fournaise profile (Figure 7a). This profile is influenced by long-wavelength anomalies (α, β, and γ) which are attributed to the regional magnetic fabric of the oceanic crust. We have not attempted to model these deep structures, because our purpose is to study the volcanic superstructure above the seafloor. The curve obtained for the island's interior model matches the shorter-wavelength anomalies in location, amplitude, and horizontal extent, but because the deeper oceanic structure is not modeled, it is slightly shifted from the observed curve.

The observed profile requires the model to include (1) highly magnetized upper formations of normal polarity, corresponding to the subaerial edifice of Piton de la Fournaise and (2) underlying reversely magnetized formations culminating beneath the northern part of the edifice. The gradient of anomaly A, above the summit, implies very high magnetization contrasts. In order to remain in a realistic, though high, range of magnetization values, we allow a stratification of the magnetization intensity distribution. The high superficial magnetization represents the youngest pile of lava flows, whereas the deeper (i.e., older) formations have a lower magnetization intensity. The presence of a shallow magma chamber and of a hot hydrothermal zone which would produce low magnetization are not supported by the magnetic data or at least do not have a signal perceptible at this scale. Although the presence of these features is strongly supported by a host of

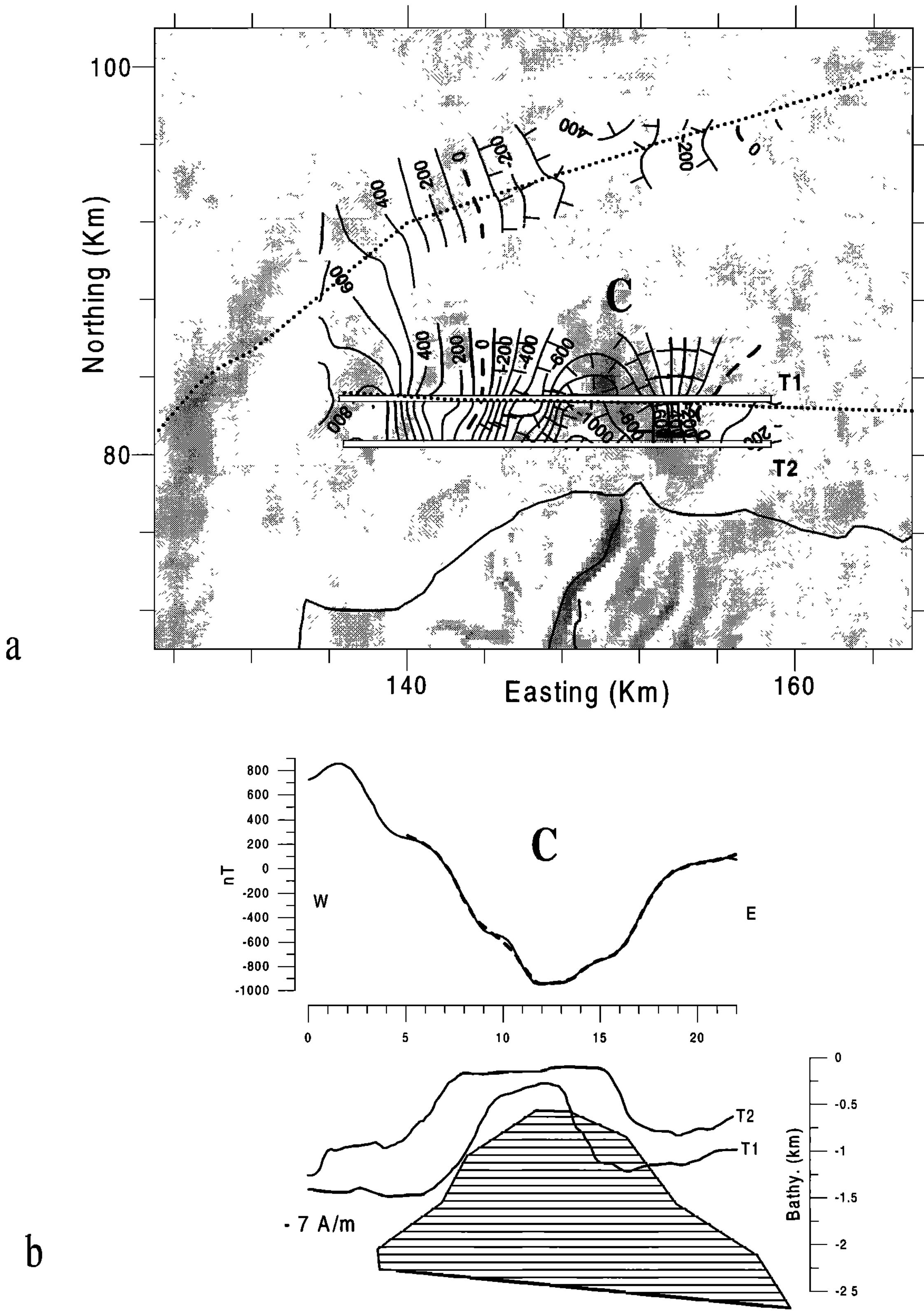

Figure 6. Interpretation of the sea level RTP magnetic anomaly near the northern seashore. (a) anomaly map superimposed on shaded bathymetry. C is the anomaly discussed in the text. T1 and T2 are the locations of the bathymetric profiles for Figure 6b. Magnetic contours are 100 nT. Black dots show location of the magnetic measurements along the ship track. (b) Bathymetric and magnetic profiles of anomaly C along lines T1 and T2; dashed line, 2-D model profile.

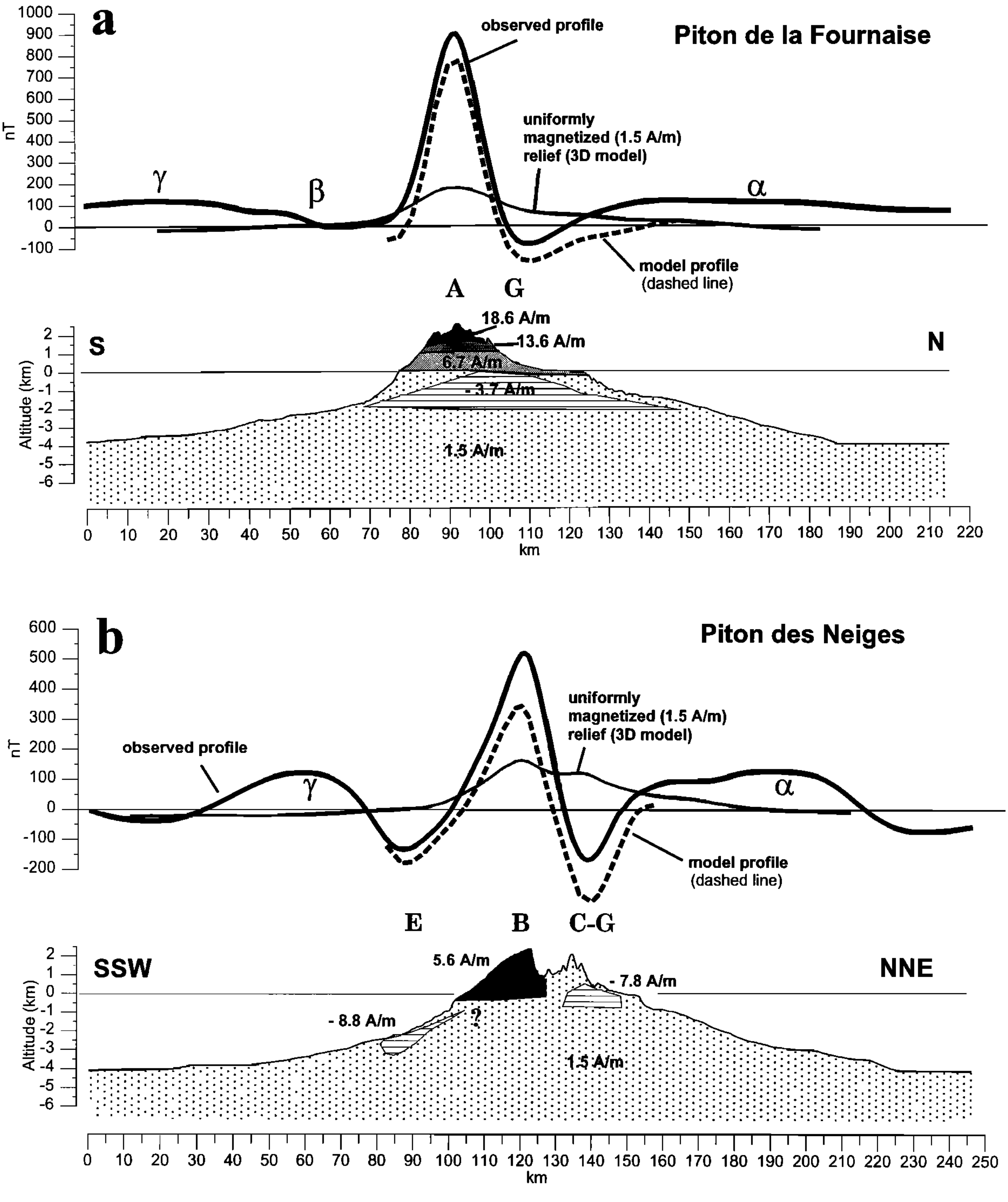

Figure 7. Interpretation of the RTP anomaly profiles across the island (see Plate 1e) at 7500 m asl. The effects of the 2.5-D structures (extending 10 km on both sides of the profiles) are superimposed on the relief anomaly estimated in three dimensions (see text). (a) A 2.5-D model across Piton de la Fournaise. (b) A 2.5-D model across Piton des Neiges.

other geological and geophysical observations [*Lénat and Bachèlery*, 1990; *Lénat et al.*, 2000], it is clear that their dimensions are not large enough to affect the magnetic data. They could be resolved only by finer-scale analysis of magnetic data over the central area of Piton de la Fournaise. Although the interpretation of the magnetic low G on the north flank of Piton de la Fournaise requires the presence of a reversely magnetized structure, its shape is not well constrained in this model.

4.5.2. Piton des Neiges profile (Figure 7b). This profile is also influenced by long-wavelength anomalies (α and γ), and the same considerations as above (Piton de la Fournaise profile) apply to the calculated curve. The simplest interpretation of this profile requires three magnetic bodies: (1) a pile of relatively highly magnetized formations having normal polarity (anomaly B), (2) a reversely magnetized structure (anomalies C and G) to the north, and (3) another reversely magnetized structure (anomaly E) to the south. Like the case for Piton de la Fournaise, the modeled structures here are poorly constrained at depth. This model agrees well with the qualitative interpretation and the sea level models developed above. We note that the dense hypovolcanic complex revealed by gravity (Figure 3b) does not have any obvious magnetic signature.

5. Discussion

5.1. Distribution of Predominantly Normally and Reversely Magnetized Formations

The strong negative anomalies near the eastern, southwestern and northern shores of the island provide evidence that reversely magnetized formations are present at the base of the subaerial formations in these areas. On land, negative anomalies C, D and G are coincident with outcrops of rocks older than 0.78 Ma but also extend over areas larger than those outcrops. We infer that the cap of rocks younger than 0.78 Ma in the areas C, D, and G is minor above a larger volume of reversely magnetized formations. This interpretation is illustrated by the models in Figure 7. The two main positive anomalies A and B correspond to a large part of Piton de la Fournaise edifice and to a thick pile of normally magnetized rocks on the western flank of Piton des Neiges (Figure 7), respectively.

From these observations we can construct a map showing the distribution of predominantly normally and reversely magnetized formations within Réunion. The resulting pattern (Figure 8) differs strikingly from the one expected from previous models of the island's evolution. In those models the evolution of Réunion was regarded as the growth of two volcanoes, Piton des Neiges first (from > 2 Ma to 12 ka) and Piton de la Fournaise later (~ 0.5 Ma to present) on the east-southeast flank of Piton des Neiges. But according to Figure 8, prior to 0.78 Ma the island would have had a surface area at least comparable to the present one, with anomalies C, E, and H1 possibly marking elongated volcanic rift zones.

5.2. Piton des Neiges

The general morphology of Piton des Neiges is far from that of a pristine, unmodified volcano (Figure 2). Erosion in a tropical environment for more than 2 Myr during its subaerial evolution must be regarded as one of the main agents leading to the present topography and landforms. The three main "Cirques" (Mafate, Salazie, and Cilaos) are usually regarded as erosional features, possibly influenced by tectonics (see a summary by *Kieffer* [1990b]). There is, however, an obvious difference between the comparatively pristine topography of the western flank of the massif and its highly dissected and jagged northern, eastern, and southern areas. This difference cannot be explained solely by the difference in rainfall between the windward (ENE) and leeward (WSW) sides of the island, because in that case the south flank of the massif would not look much different than the west flank. This large-scale contrast in topography is certainly related primarily to its volcano-tectonic history, which has led to the preservation of a more regular pile on the western flank than in other areas.

From gravity data [*Malengreau et al.*, 1999] we know that the central part of Piton des Neiges is underlain by a large dense body, extending from virtually the bottom of the "cirques" to depths of several kilometers. This dense mass represents the core of the volcano and is thought to consist of hypovolcanic bodies (sheet intrusions, gabbros, and cumulates) which crop out in a few places. Following *Ryan* [1987], we infer that the large vertical extent of the dense body implies that Piton des Neiges has remained a stable locus of activity since the early stages of Réunion volcanism. The dense complex developed upward as Piton des Neiges grew.

The morphology of submarine flanks surrounding Réunion suggest that those flanks are accumulations of landslide debris instead of lava flows. This has been confirmed by detailed studies of the eastern submarine flank [*Lénat et al.*, 1990; *Labazuy*, 1996] and by seismic surveys [*de Voogd et al.*, 1999]. Virtually all the dredged samples in this area are fragments of subaerially erupted lavas, indicating that the source areas of the landslides were on land. Four or five other large bathymetric bulges on the submarine flanks may be associated tentatively with source areas on land (Figure 8). Piton des Neiges therefore must have undergone major episodes of destruction during its evolution. The recurrence of these lateral collapses may account for the apparently complicated geology of Piton des Neiges. For example, the apparent 700 ka (from 1.9 to 1.2 Ma) and 400 ka (from 950 to 578 ka) interruptions of volcanism of the shield [*McDougall*, 1971] could be artifacts of accumulation in restricted sectors during these intervals. The lava flows erupted at these times may have accumulated within landslide depressions (like now in the Enclos-Grand-Brûlé system of Piton de la Fournaise) and are now concealed by later accumulations.

None of the landslides from Piton des Neiges suggested on Figure 8 have yet been recognized on land, but subaerial landslide products have been recognized in the Cap La Houssaye area [*Bachèlery et al.*, 1996] and at the bottom of Cilaos Cirque [*Maillot*, 1999]. Anomaly B tells us that a thick pile of Brunhes-age volcanic products has accumulated in the western part of Piton des Neiges and has remained virtually undisturbed. This pile may have accumulated in a depression left by westward-directed landslides. The smaller thicknesses of Brunhes-age products on other parts of Piton des Neiges could have resulted from channeling into the western structure or that such accumulations have been eroded by recent flank landslides.

5.3. Takamaka Volcano

Inference of a concealed volcanic center beneath anomaly G stems from combining gravity and magnetic observations. Modeling of gravity data from the area of anomaly G [*Malengreau et al.*, 1999] shows the presence of a dense body rising to less than 1 km beneath sea level and extending downward a few kilometers, though to smaller depths than the dense body beneath Piton des Neiges. Magnetic anomaly G reflects the presence of an underlying large volume of predominantly reversely magnetized rocks. This is compatible with pre-Brunhes accumulation of volcanic products around an hypovolcanic complex. In addition, seismic studies [*Charvis et al.*, 1999] reveal a high-velocity zone in agreement with the gravity observations. Although no geological data are presently available to support the existence of Takamaka volcano, the various geophysical observations provide enough evidence to infer the former existence of a volcanic center in this area. However, because of the presumed depth of this system, it is probable that only drilling could provide a definitive answer for the existence of Takamaka volcano.

5.4. Piton de la Fournaise and Les Alizés Volcanoes

The existence of the dense complex beneath Grand-Brûlé (Figure 3b), near the eastern shore of the island, long stood as an enigma, since no volcanic system had been recognized in this area. It could not be associated with Piton de la Fournaise because there is a significant distance between the two centers.

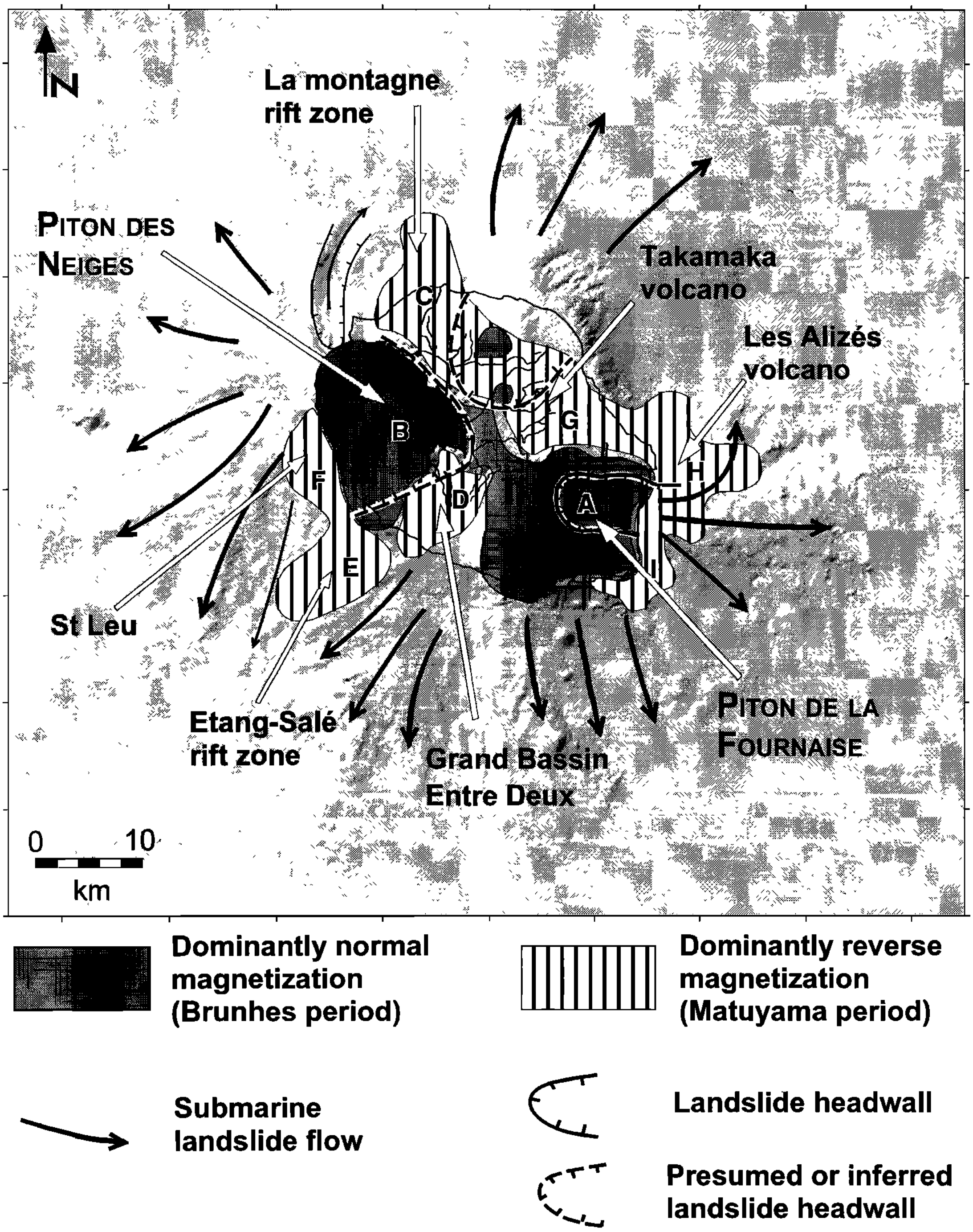

Figure 8. Structural map of Réunion showing the inferred distribution of Matuyama and Brunhes formations and landslides.

The deep geothermal exploration drill hole [*Rançon et al.*, 1989] penetrated the dense body from a depth of 1000 m to the bottom of the well at 3000 m and established its hypovolcanic nature. Gravity models suggest its vertical extent to be similar to that of the dense complex of Piton des Neiges [*Rousset et al.*, 1989; *Malengreau et al.*, 1999]. Accordingly, using the same rationale as for Piton des Neiges Complex, we infer that the Grand-Brûlé complex represents a volcanic center that began to grow in the early stages of Réunion volcanism. Studies of similarly active basaltic shields [e.g., *Ryan*, 1987] indicate that the tops of intrusive complexes are located at depths of 2 to 4 km beneath the surface. Therefore with the top of Grand-Brûlé complex at about 1000 m beneath the present surface, the corresponding volcanic edifice should have been emerged by 1000 m or more when it was active. Our magnetic data indicate for the first time the presence of old (i.e., < 0.78 Ma) constructional volcanic features at shallow depth in the vicinity of the Grand-Brûlé complex. We will now attempt to draw a model commensurate with the available observations.

Magnetic anomalies H and I, associated to pre-Brunhes formations at shallow depth, surround the Grand-Brûlé complex to the east. We suggest that they are the remnants of an edifice associated with the hypovolcanic complex. We name this inferred edifice Les Alizés volcano (note that *Rançon et al.*

[1989] speculated previously that the Grand-Brûlé complex belonged to a "proto-Fournaise" volcano, but the submarine topography which they interpreted as the flank of their "pro-Fournaise" volcano has now been proved to consist of slumped material). In our interpretation the context of Piton de la Fournaise is very different from the previous view of it as a young volcano growing on the flank of Piton des Neiges. Piton de la Fournaise probably is a young locus of activity, since the gravity data reveal that it has not yet developed a large hypovolcanic complex. But it began to grow on the flank of Les Alizés volcano instead of Piton des Neiges. With the flanks of Takamaka and Piton des Neiges volcanoes to the north and the NW, respectively, Piton de la Fournaise was buttressed on all sides except to the south. The questions that arise from this model are (1) What happened to the edifice of Les Alizés volcano ? and (2) Why are Piton de la Fournaise landslides directed toward the east ?

From seismic studies, *de Voogd et al.* [1999] found that thick layers of landslide debris form the bulk of the eastern and southern submarine flanks of Piton de la Fournaise. This is in agreement with morphological studies of those areas [*Lénat et al.*, 1990; *Labazuy*, 1996] (Figure 1). To the east, surficial deposits are related unambiguously to Piton de la Fournaise, but the presence of older material (i.e., from Les Alizés) deeper in the thick pile of landslide material is probable. To the south, landslide-derived formations extend down to the oceanic basement. The provenance of the debris in this area is not established. We suspect that Piton de la Fournaise has contributed some of these deposits, because the morphology of its subaerial south flank (Figure 2) suggests the presence of buried landslide scars. The subaerial south flank is less regular than the north flank, being eroded by large valleys, a difference that is anticorrelated with the rainfall on the opposing flank. But the large volume of landslide deposits requires additional sources of south-flank debris. This suggests Les Alizés volcano had already produced voluminous landslides prior to growth of Fournaise. If so, the edifice of Les Alizés volcano must have lost much of its volume to mass wasting, and perhaps this can explain the disappearance of most of that edifice above the Grand-Brûlé complex.

With its flanks buttressed in all directions except the south, Piton de la Fournaise should have been prone to landslides directed only to the south. The eastward direction of its recent landslides can only be explained if a former structure has played an influence. The width of the landslide scar on the subaerial east flank of Piton de la Fournaise matches that of the hypovolcanic complex of Les Alizés volcano (Figure 3b), and the top of the complex in the drill hole is thought to coincide with the base of the landslides [*Labazuy*, 1991; *Courteaud*, 1996]. It therefore seems likely that a mechanical discontinuity coincides with the top of the hypovolcanic complex. That discontinuity is likely to be a hydrothermally altered zone, similar to those typically developed above hypovolcanic complexes. Such zones have low cohesion and are often considered as potential rupture loci for landslides on volcanoes [*Siebert*, 1984]. We hypothesize therefore that the eastward

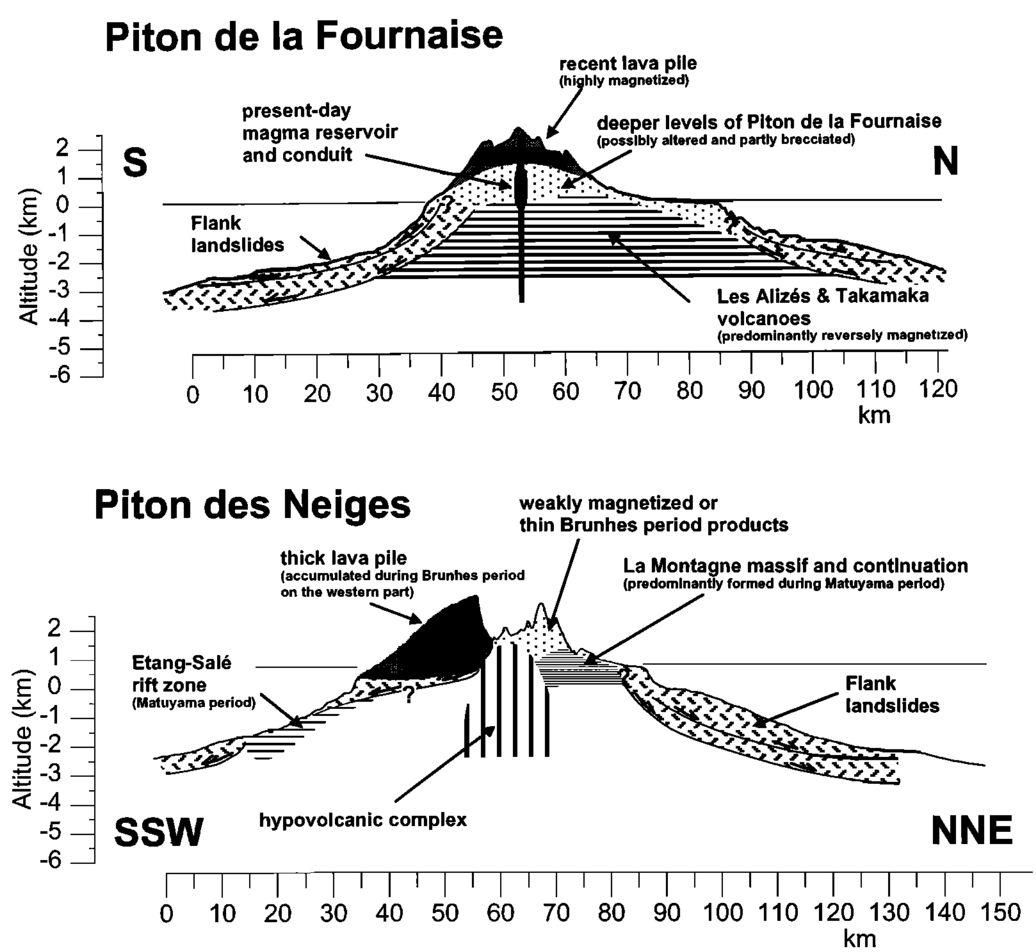

Figure 9. Interpretative crosssections of Piton de la Fournaise and Piton des Neiges summarizing the interpretations discussed in text.

moving landslides of Piton de la Fournaise were caused by a rupture in the hydrothermally altered zone of Les Alizés volcano. These events could have further denuded the Les Alizés edifice and contributed to instability of the eastern flank of Piton de la Fournaise.

We suggest that the horseshoe-shaped depression produced by eastward directed landslides influenced the development of the NE and SE rift zones of Piton de la Fournaise, as a gravitational response to the altered shape of the edifice, according to the *Fiske and Jackson* [1972] model. Similarly, the old Ilet Edouard rift zone (Figure 2) [*Bachèlery and Mairine*, 1990] could have developed earlier in response to flank landslides directed toward the south.

6. Summary and Conclusion

The interpretation of airborne and marine magnetic data over Réunion allows us to propose a new model for the volcanic evolution of Réunion, as summarized on Figures 8 and 9. The deep submarine flanks of Réunion are poorly magnetized, exhibiting no magnetic features of substantial width or amplitude except in special areas near the shore. This strongly suggests that the submarine flanks are composed mostly of poorly magnetized material. That material probably is chaotic landslide debris, which in bulk measurement shows only induced and viscous magnetization because the vector sum of the thermoremanent magnetizations of the innumerable rotated fragments is statistically null. This conclusion is consistent with geologic evidence that flank mass-wasting events are major and general processes in the growth of oceanic shield volcanoes [*Holcomb*, 1990; *Holcomb and Searle*, 1991; *Moore et al.*, 1994].

In contrast, the core of the island is composed of highly magnetized rocks. Some large areas are composed mostly of reversely magnetized rocks, and two areas are composed of normally magnetized rocks. This pattern shows that at the Matuyama-Brunhes reversal (0.78 Ma) the island consisted of at least two main volcanoes: Piton des Neiges to the WNW and Les Alizés volcano to the ESE. Each volcano has a large, deeply rooted hypovolcanic complex indicating that it was a long-lasting locus of volcanic construction. The presence of a third, Takamaka, volcano at the north-center of the island is strongly supported by gravity, seismic, and magnetic data. Piton de la Fournaise grew on the flank of Les Alizés volcano and is a relatively young focus of volcanism.

The large volume of chaotic, poorly magnetized debris around Réunion indicates that volcanoes of the island have experienced large flank collapses in all directions. In the area of Piton des Neiges, no large landslide structures have yet been recognized on land, but the magnetic data suggest that a large scar in the western flank may have been filled by Brunhes-age lavas. In the Alizés-Piton de la Fournaise area, only the recent landslides of the flank of Piton de la Fournaise toward the east are clearly identifiable on the surface. The coincidence between the width of these landslides and that of the Grand-Brûlé hypovolcanic complex leads us to propose that the slides were caused by failure in a zone of low cohesion in hydrothermally altered rocks above the hypovolcanic complex, producing an instability in the eastern flank of Piton de la Fournaise that played a major role in the volcano's evolution. This instability can explain the westward migration of the volcano center [*Bachèlery and Mairine*, 1990; *Bachèlery and Lénat*, 1993] and the development of its NE and SE rift zones.

The analysis of the magnetic anomalies over Réunion was an essential step in defining this new model for the evolution of the volcanism of the island. The discussion herein does not include all consequences of the new model of the island, but it provides a basis for reinterpretation of previous data and defining future studies. This study also illustrates the potential of magnetic data for deciphering the structure of similar volcanoes whose evolution spans reversals of geomagnetic polarity.

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