2 Geodynamic Setting of La Réunion

Jean-François Lénat

Abstract

The island of La Réunion is located in the complex oceanic environment of the Marscarene Basin. The latter was created by oceanic expansion between the late Cretaceous and the Paleocene. The expansion of the Basin stopped at magnetic chron 27 when the spreading jumped north, between the Seychelles and India, to become the Central Indian Ridge. Dating and geodynamic reconstructions support a hot spot origin for La Réunion volcanism. La Réunion lies in the middle of an approximately 350 km-wide zone bounded by transform faults (Mauritius and Mahanoro-Wilshaw Fracture Zones) and a trough identified as the extinct spreading center (chron 27). This compartment exhibits a substantial depth anomaly (several hundreds of meters), possibly related to the interaction with the hot spot plume. Gravity and seismic data show the virtual absence of flexure beneath and around La Réunion. Near La Réunion the organization of the oceanic crust magnetic anomalies is very different from the classic parallel striped oceanic organization. It has been suggested that this pattern might be interpreted in terms of a paleo-triple junction of oceanic rifts. Many seamounts protrude from the sediments in the La Réunion segment, some associated with the transform faults, others associated with a series of parallel ridges and a few isolated others. All these constructions postdate the oceanic crust, but most of them appear to be much older than La Réunion, with the possible exception of some small seamounts close to La Réunion or on its submarine flanks.

2.1 Regional Tectonic Setting

The Indian Ocean started to open up around 175 Ma (Schettino and Scotese 2005). The early stages of Gondwanan break-up separated Africa from a block composed of Madagascar, India, Australia and Antartica (Coffin and Rabinowitz

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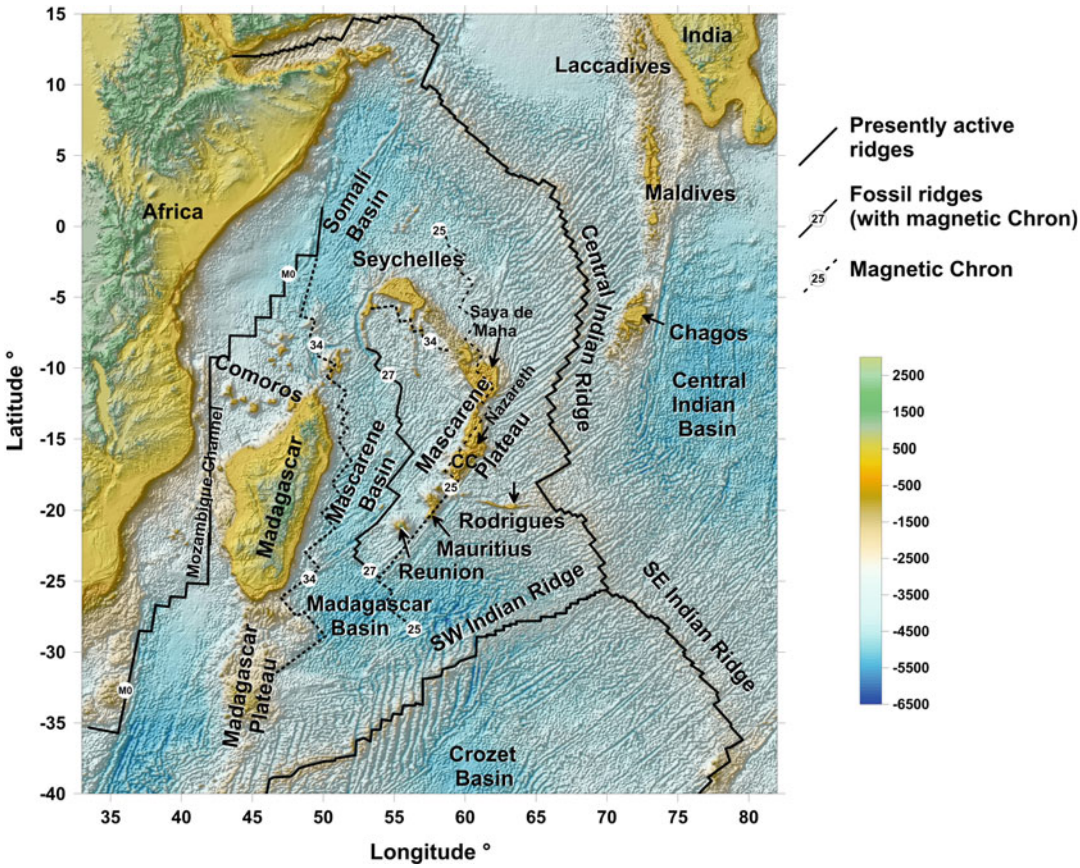

Fig. 2.1 Geodynamic setting of the Comoros and La Réunion. The magnetic chrons are taken from Müller et al. (1997)

1987; Smith and Sandwell 1997). This first rift became inactive at about 120 Ma (magnetic chron M0; Fig. 2.1). It opened the Mozambic Channel in which the magmatism of the Comoros archipelago would develop later (Michon 2016, Chap. 21). Around 83 Ma (magnetic chron 34), the Mascarene Basin (Fig. 2.1) opened, marking the separation of Madagascar and India (Bernard and Munschy 2000; Dyment 1991a). The Mascarene Basin rift became extinct at anomaly 27 ($\sim$61 Ma), when the spreading jumped to a new location, between the Seychelles and India, to become the Central Indian Ridge. Nowadays, La Réunion and the Comoros Archipelago lie on the Somalian plate, which is bounded by the Central and SW Indian ridges to the east and south and by the East African Rift to the west (Stamps et al. 2008).

It is easy to pick out the plateau features on Fig. 2.1, and they can be divided into continental and oceanic areas. The Seychelles and Madagascar are micro-continents isolated by the episodes of sea floor spreading described above. Torsvik et al. (2013) suggest that additional continental fragments are present beneath part of the Saya de Maha and Nazareth Banks, Cargados-Carjos and Mauritius, forming an arc of anomalously thick crust that extends northwards from Mauritius to the Seychelles. The other plateaus, Laccadives, Maldive, Chagos, Mascarene, and Mauritius and La Réunion islands, are widely regarded as volcanic constructions of the La Réunion hotspot which can be traced back to the emission of the Deccan Trapps in the late Cretaceous era. This hypothesis is supported by dating and geodynamic reconstructions (Duncan 1990; Duncan et al. 1989; Georgen et al. 2001; Storey 1995). When the hotspot was near the mid-ocean spreading ridge, it produced complex structural and geochemical interactions (Ito et al. 2003; Morgan 1978; Sleep 2002). For example, the Rodrigues Ridge is interpreted as the result of the interaction between the Central Indian Ridge and the Réunion hotspot (Füri et al. 2011; Morgan 1978; Nauret et al. 2006).

The structure of the Mascarene Basin has been the subject of numerous studies since the 1970s because it is a key area to understand the geodynamics of the early stages of the Indian Ocean. The structure and evolution of the northwestern end of the Basin is still poorly known, although recent works (Bernard and Munschy 2000; Collier et al. 2004; Fretzdorff et al. 1998; Todal and Eldholm 1998) have provided significant new knowledge. Various models have been proposed over the years. Bernard and Munschy (2000) suggest that the Mascarene Basin is composed of 9 zones separated by major transform faults. Their geometry implies two different rotation poles (between 83 and 67.7 Ma, and between 67.7 and 59 Ma). The magnetic anomaly pattern suggests a progressive southward extinction of the spreading center (67 Ma in the north and about 61 Ma in the south).

2.2 La Réunion and the Surrounding Lithosphere

2.2.1 Characteristics of the Oceanic Compartment of La Réunion

La Réunion lies in the middle of an approximately 350 km-wide zone bounded by the Mauritius transform fault (Mauritius Fracture Zone or FZ) to the SE and by the Mahanoro-Wilshaw transform fault (Mahanoro-Wilshaw Fracture Zone or FZ) to the NW (Fig. 2.2a). Another structural boundary, to the SW, is a trough identified as an extinct spreading center (magnetic anomaly 27).

2.2.1.1 Bathymetry Anomaly

A distinctive characteristic of this compartment is its anomalous bathymetry (Fig. 2.2a). The shallow bathymetry of the compartment was first mentioned by Bonneville et al. (1988). Lénat et al. (2009) have analysed this anomaly by comparing the actual bathymetry corrected for sediment load with a theoretical bathymetry based on the thermal subsidence of the oceanic lithosphere as a function of its age. They found a substantial depth anomaly, reaching several hundreds of meters, bounded by steep gradients corresponding to the transform faults and the fossil ridge. These authors have carried out analogue modelling to explore the deformation resulting from a mantle plume rising beneath a faulted lithosphere. The scale models suggest that the most important factor controlling the buoyant flow of the plume material is the presence of mechanical discontinuities (transform faults and an extinct ridge) at the lithospheric scale, which allow a complete decoupling of the deformation on their two sides. Such a model could account for the anomalous bathymetry of the La Réunion compartment where the upward flow of the plume material would be trapped in the zone bounded by the lithospheric discontinuities and accommodated by deformation within this zone. As we will see later, this mechanism could contribute to the dynamic support of La Réunion, where virtually no lithospheric flexure exists. Note that Bonneville et al. (1997), Michon et al. (2007) also suggested a dynamic support by the mantle plume beneath La Réunion.

2.2.1.2 Gravity and Magnetic Patterns

Gravity

Figure 2.2b shows a free air gravity map from Sandwell and Smith (2009). Gravity is better than bathymetry for highlighting the features of the oceanic crust where there is a blanket of lightweight sediments (abyssal plains,

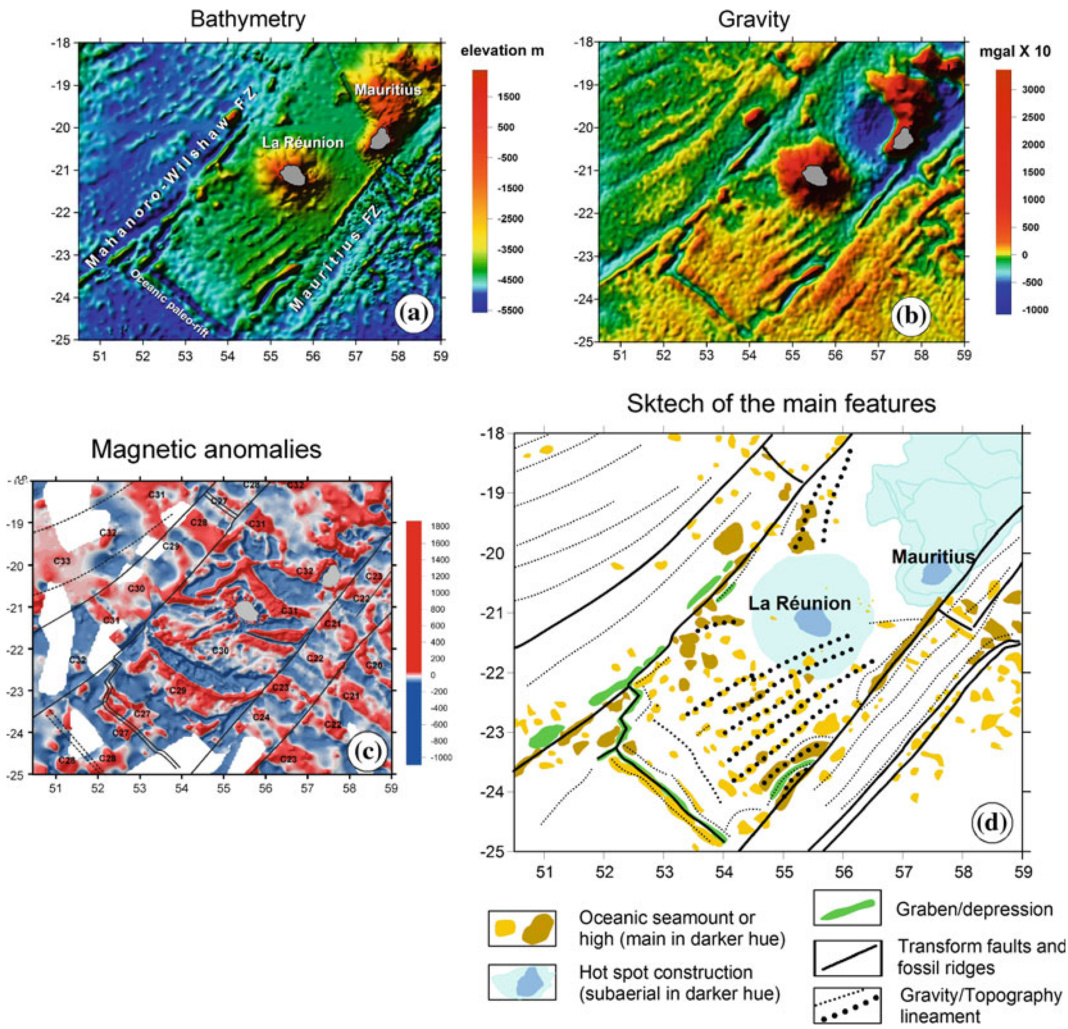

Fig. 2.2 **a.** Shaded topography of the La Réunion zone (Smith and Sandwell 1997). **b** Shaded free air gravity (Smith and Sandwell 1997). **c** Magnetic anomaly map. Magnetic chrons from Bernard and Munschy (2000), Dyment (1991b). **d** Structural plan of the area

topographic depressions filled with sediment, etc.). The short wavelength features observed on the bathymetry are therefore better defined on the gravity, which also reveals some lineaments that were less perceptible on the bathymetry (2.2a). The large range of gravity values in this area of the map is related to the presence of the islands and of large seamounts for the positive values, and to the presence of sedimentary basins along transform faults and around Mauritius for the negative ones. Note that to the SW of La Réunion (and further to the S and SE) there are positive values that suggest poor isostatic compensation. The load of Mauritius has induced a flexure of the lithosphere which has been filled by sediments. This is well documented by the gravity and seismic data acquired during the FOREVER cruise in 2006 (de Voogd et al. 2009). Conversely, it has been shown by gravity and seismic data acquired during various cruises (Charvis et al. 1999; de Voogd et al. 1999, 2009; Gallart et al. 1999) that no flexure and corresponding sediment filling is observed beneath and around La Réunion.

Magnetics
In the La Réunion compartment, the authors (Bernard and Munschy 2000; Dyment 1991a; Fretzdorff et al. 1998) were confronted with difficulties in trying to establish the location and identification of the magnetic chrons, partly because of inadequate data coverage, but above all because of the complexity of the anomaly pattern. Recently, Bissessur (2011) has used newly acquired data from the FOREVER and ERODER 1 and 2 cruises (Deplus et al. 2007; Savoye et al. 2008) to propose a more complete analysis and interpretation of the history of the oceanic crust in this area. Figure 2.2c shows a magnetic anomaly map of the area. The anomalies are now very well defined near La Réunion, and to different degrees in the other areas, depending on the available data. Figure 2.2c clearly shows that near La Réunion the organization of the oceanic crust anomalies departs drastically from the classic oceanic organization into parallel stripes, as is observed beyond the La Réunion compartment. In the bottom left of the figure the authors identify a traditional pattern of anomalies with a ridge jump at chron 28 (~63 Ma) and an extinct rift at chron 27 (~61 Ma). Then towards the northeast of the compartment, the pattern of anomalies 29 to 32 becomes complex, with different and varying orientations. Bissessur (2011) interprets this pattern as the result of a triple junction of oceanic rifts. He identifies this junction with the Indian Ocean Triple Junction (its present location can be seen on Fig. 2.1) that would have been located in the Mascarene Basin before anomaly 29 (~64–65 Ma).

2.2.1.3 Seamounts and Sediments of the Oceanic Plate

As compared to the predicted bathymetry (Smith and Sandwell 1997), from which the structural plan of Fig. 2.2d is drawn, the description of the submarine part of La Réunion and its surrounding oceanic environment has been drastically improved recently thanks to high resolution bathymetric and acoustic mapping and seismic profiling. FOREVER and ERODER 1 and 2 cruises (de Voogd et al. 2009; Deplus et al. 2007; Savoye et al. 2008) in 2006 and 2008 were instrumental in providing a homogeneous

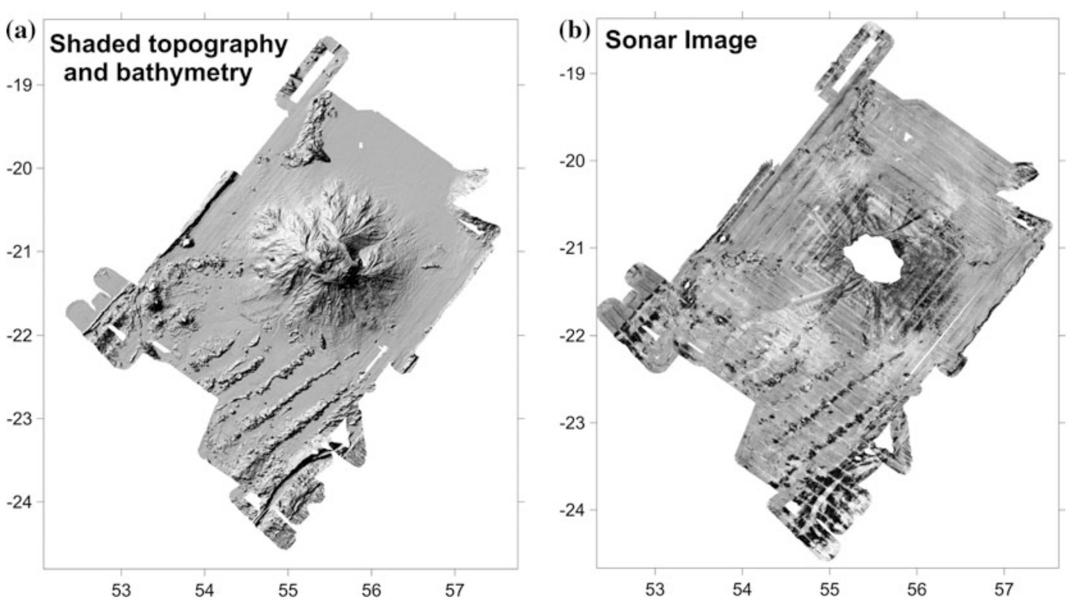

Fig. 2.3 **a** shaded bathymetry, and **b** acoustic images from forever and eroder cruises (Deplus et al. 2009; Savoye et al. 2008)

coverage of a large part of the La Réunion compartment (Fig. 2.3).

Many seamounts protrude from the sediments in the La Réunion segment (Figs. 2.2a, d and 2.3). We can distinguish those associated with the transform faults and those associated with a series of parallel ridges. A few others, however, are more difficult to link to those categories.

The Mahanoro-Wilshaw and Mauritius transform faults are only partially mapped by high resolution bathymetry (Fig. 2.3), but the predicted bathymetry of Smith and Sandwell (1997) provides complete low resolution coverage. Linear ridges and grabens are observed along the transform faults. Studies in various places suggest that magmatic activity can take place at transform faults near spreading centers or by interaction with hotspot plumes (Hekinian and Bideau 1995; Lowrie et al. 1986; Pockalny et al. 1997). Another classic interpretation for uplift and subsidence along oceanic transform faults is differential thermal subsidence and bending (Sandwell and Schubert 1982) or shear heating and lateral heat conduction across the fault (Chen 1988) when two lithospheres of different age are brought into contact. The difference in age between the La Réunion zone and that to the NW of the Mahanoro-Wilshaw FZ ranges from 0 to 10 Ma, whereas contrasts of 15–25 Ma occur across the Mauritius FZ. However, similar age contrasts exist across other transform faults in the vicinity of the La Réunion zone without creating such marked signatures in the topography, except for the branch of the Mahanoro-Wilshaw FZ that goes to Madagascar. The constructions on the transform faults forming the borders of the La Réunion segment are mostly straight ridges, apparently incised longitudinally by the faults. Theses ridges may act as barriers to the sediments. For example, we note that the bathymetry between the foot of La Réunion and the Mauritius transform fault is not flat but decreases gently toward the fault, suggesting that deposits from La Réunion extend down to the foot of the ridge, possibly as fine sediments derived from landslides.

To the S-SW of La Réunion, a series of ~50°N trending ridges (Figs. 2.2a, d and 2.3) constitutes one of the main topographic characteristics of the oceanic crust in the La Réunion compartment. They are quasi-periodic features, separated from each other by ~35 km. They are more or less continuous and apparently formed by continuous coalescence of individual seamounts of variable dimension and height. Some of the seamounts are isolated features, but this may be an artifact due to the burial of the area by sediments, under which they may be coalescent. Near the Mahanoro-Wilshaw fracture zone, the ridge pattern becomes less clear. Two very large seamounts are observed in this area. At the latitude of La Réunion, a less focussed ~N90 ridge extends from near the Mahanoro-Wilshaw fracture zone and disappears beneath the western submarine flank of La Réunion. On the other side of the island, a large elongated seamount is in line with the ~90°N ridge. Along this line, we also observe a seamount protruding from the western flank of La Réunion. It has been studied by Oehler et al. (2008) and named Sonne Seamount. The ridges and their sedimentary environment have been studied by Fretzdorff et al. (1998), de Voogd et al. (2009), Deplus et al. (2009). The ridges and seamounts protrude from a flat seafloor covered by a few hundred meters of sediments. The morphology of their flanks, their sediment cover and the coating of the dredged samples by Mn-oxides (Fretzdorff et al. 1998) indicate that they are old seamounts. The seismic data show that the sedimentary sequence is deformed and disrupted in several places (de Voogd et al. 2009). The ~50°N and ~90°N elongation of the ridges is significantly different from that of the transform faults (~35–40°N). They clearly intersect the magnetic fabric of the oceanic crust and must therefore be regarded as being younger than the oceanic crust. Linear ridges, oblique to transform faults and the oceanic ridge, have been described in several places (e.g. in the South Pacific between the Louisville chain and the ridge (Small 1995), or the Musicians Seamounts (Kopp et al. 2003)). Most authors now agree that the ridges represent plume channels between a hot spot and an oceanic rift. Thus Bissessur (2011) proposes that these ridges would result from interaction between the nascent

La Réunion hot spot, around 65 Ma, and the Mascarene Basin rifting, until the latter vanished when the rifting jumped north to the Carlsberg ridge.

It is clear that some of the ridges intersect La Réunion and should be present beneath the edifice, but they do not reappear at the north. Processing of the seismic data acquired during the FOREVER and ERODER cruises should show whether or not they do reach that far, or if they are buried by the sediments which are thicker there (de Voogd et al. 2009). We also note the presence of a large seamount partialy buried by the edifice of La Réunion to the south. This seamount is in the continuation of a 50°N ridge, but has an elongation at nearly right angles to the ridge. The interferences between these oceanic constructions and the construction of La Réunion are still unexplored. At the least these positive reliefs have probably acted as topographic barriers during the evolution of the submarine slopes of La Réunion, and Oehler et al. (2008) document some cases where La Réunion products are impounded by ocean seamounts. Finally, to the north, near the Mahanoro-Wilshaw fracture zone, a large ridge could be related to the transform fault system. At its southern tip there is a substantial seamount with a clear 120°N elongation.

A different type of individual seamount is observed to the north-east of the island (Oehler et al. 2008) (Fig. 2.3). These seem to have a pristine morphology and are well-shaped flat-topped seamounts. Oehler et al. describe two of them that appear to have grown on the lower submarine flank of La Réunion and must therefore be young constructions.

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