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Structure of Réunion Island (Indian Ocean) inferred from the interpretation of gravity anomalies

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Abstract

Réunion is a volcanic edifice whose origin is related to a hot spot in the Indian Ocean. Only 3% of its volume is emergent. Many geological and geophysical studies were carried out on Réunion Island during the 1980's but few of them allow study of the internal structure of the edifice. Several gravity surveys have been carried out on the island since 1976 and we have compiled the available data set. The lack of data on the western side of the island led us to conduct a regional survey in 1993 to obtain a more homogeneous distribution of the stations. Computation of Bouguer anomalies for different correction densities accounts for the variable density of the rocks constituting the edifice and provides a distribution of gravity anomalies interpreted as dense bodies of intrusive rocks inside the edifice. Two very large intrusive complexes can be unambiguously recognised: one beneath Piton des Neiges and one beneath the Grand Brûlé area. Both have been penetrated by geothermal exploration drill holes and the first is also known from outcrop observations. 2.5D simple models were constructed to reveal the geometry and extent of the buried intrusives. They are deeply rooted, extending several kilometres below sea level, and extensive (20–25 km long and 10–13 km wide for the Piton des Neiges complex, 12–15 km long and some kilometres wide for the Grand Brûlé complex). The development of such complexes implies that the activity of the two volcanic centres was long lasting and remained stable while the volcanoes were growing. The Grand Brûlé complex has been interpreted as relics of an old volcano named Alizés Volcano. The interpretation of the gravity maps suggests the presence of a ridge of dense rocks to the North of the axis joining the centres of Piton des Neiges and Piton de la Fournaise volcanoes. By analogy with the other structures, 2.5D models show that this structure would culminate between 0 and 1 km below sea level and be 15 km wide. This complex induces a maximum anomaly in Takamaka Valley and we thus propose to name it Takamaka Volcano. No geological evidence of the nature of these dense rocks is available but the ridge coincides with structures revealed by magnetic and seismic data. Interpretation of the Bouguer anomaly maps suggests that the inner gravity structure of Piton de la Fournaise is not characterised by the presence of a voluminous dense body but

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probably by more restricted concentrations of dense rocks. Some structures can be recognised: along the present NE and SE rift zones and in the previous central part of Piton de la Fournaise to the West of the present summit. The recent eastward migration of the centre of activity of Piton de la Fournaise accounts for the lack of a large positive anomaly beneath the active craters.

Keywords: Réunion Island; Indian Ocean; gravity anomalies

1. Introduction

Oceanic islands are volcanic edifices that usually evolve over several million years. Only part of their history is accessible because only the last stages of their growth are exposed. Geophysical prospecting provides a partial solution allowing the study of the internal structure of a volcanic edifice.

Réunion Island has been the subject of numerous geological and geophysical studies since the 1980's (see Special Issue of Journal of Volcanology and Geothermal Research, volume 36, 1989, or Lénat, 1990, for main sources of bibliography). However, the evolution of this complex volcanic system is not yet understood. One of the most crucial outstanding problems is that of the internal structure. Study of the magnetic anomalies over the island has provided the first evidence of the internal distribution of normally and inversely magnetised formations (Malengreau, 1995; Lénat et al., in revision). Seismic experiments (Charvis et al., 1997; Charvis et al., submitted) place constraints on the large scale structure of the lithosphere and on the structure of the edifice. In this paper, we present a description of the main gravity anomalies of the island. An interpretation of Bouguer anomalies, mostly qualitative and based on simple quantitative models, is also proposed and provides a better understanding of major dense structures of the island.

2. Geodynamic context

Réunion Island is located in the southernmost part of Mascarene Basin (Indian Ocean), 800 km east of Madagascar (Fig. 1). Its origin is related to the hot spot that generated the Deccan Trapps during the Cretaceous and then migrated SW creating a volcanic chain whose younger elements are Mauritius and Réunion Island (Duncan et al., 1989).

The shape of Réunion rising from the seafloor is that of a flattened cone, 200 to 240 km in diameter and about 7000 m high. The emerged part represents only a small portion of the edifice (about 3% of its volume).

The island sensu stricto is composed of two known volcanic massifs: Piton des Neiges and Piton de la Fournaise (Fig. 1). Piton des Neiges, which occupies the northwestern two thirds of the island, is a dormant volcano. Its activity started with the construction of a shield volcano that produced olivine-rich basalts whose oldest dated flows are 2.08 Ma old (McDougall, 1971). Between 330,000 and 12,000 years BP, Piton des Neiges erupted alkaline differentiated lavas (Gillot and Nativel, 1989; Deniel et al., 1992). The morphology of Piton des Neiges is characterised by a rough topography. Its central zone is occupied by three large depressions (Fig. 1) of uncertain origin but these cirques could result from an interplay between erosion and volcano-tectonic structures (calderas, volcanic landslides, etc . . .). At the south-eastern part of the island, Piton de la Fournaise, whose activity began more than 500,000 years ago (Gillot and Nativel, 1989), is an active basaltic shield volcano. The topography of Piton de la Fournaise is smoother, because of its younger age. Several episodes of landsliding towards the east occurred during its growth. Associated with the development of rift zones, they resulted in the formation of huge depressions limited by U-shaped rims. Enclos Fouqué and the NE and SE rift zones (Fig. 1) are the main features of the last major volcanotectonic episode. Most of the activity of Piton de la Fournaise has been restricted to effusive eruptions in the Enclos Fouqué and along its NE and SE rift zones.

A recent interpretation of airborne and marine magnetic data (Malengreau, 1995; Lénat et al., in revision) has inferred the presence of a third major centre of volcanic activity, called Alizés Volcano, in the Grand Brûlé area. Its activity would predate, or

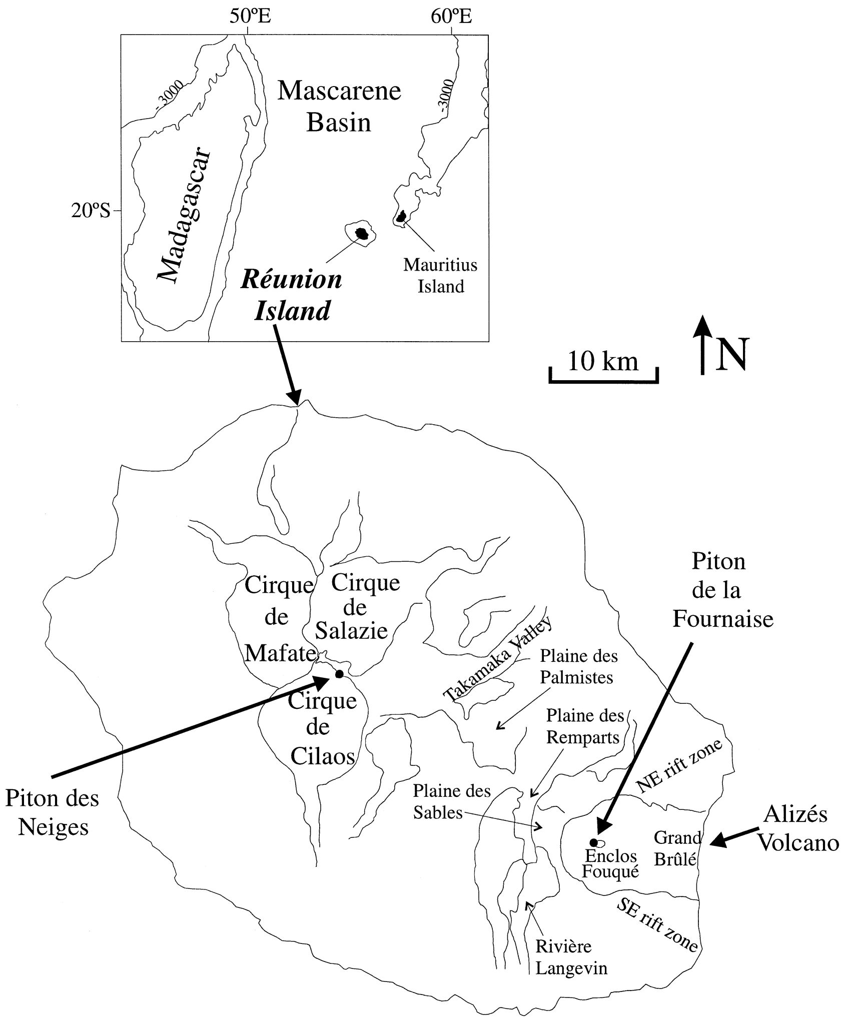

Fig. 1. Location of Réunion Island in the Indian Ocean (inset). Main topographic features of the island and location of the sites quoted in the text.

be partially contemporaneous with, that of Piton des Neiges.

3. Previous gravity studies

Several gravity land surveys have been carried out since 1976 on Réunion by groups from various French organisations (ORSTOM, BRGM, CNRS—Rechenmann, 1976; Gérard et al., 1980; Demange et al., 1989; Rançon et al., 1989; Rousset et al., 1989). By the time we started our project, the available data (Fig. 2) had been compiled by Lesquer (1990). All data were tied to the international base station of Port des Galets in the IGSN71 (absolute gravity value: 978,917.40 mGal). Data from detailed surveys in Cirque de Salazie (Demange et al., 1989), the Grand Brûlé area (Rançon et al., 1989) and offshore, the Grand Brûlé area (Rousset et al., 1987) could not be accessed for this study.

Lesquer (1990) made a first interpretation of the main structures that cause the gravity anomalies of the island. Detailed work in specific areas have also been published: eastern offshore part of Piton de la Fournaise (Rousset et al., 1987), Grand Brûlé area

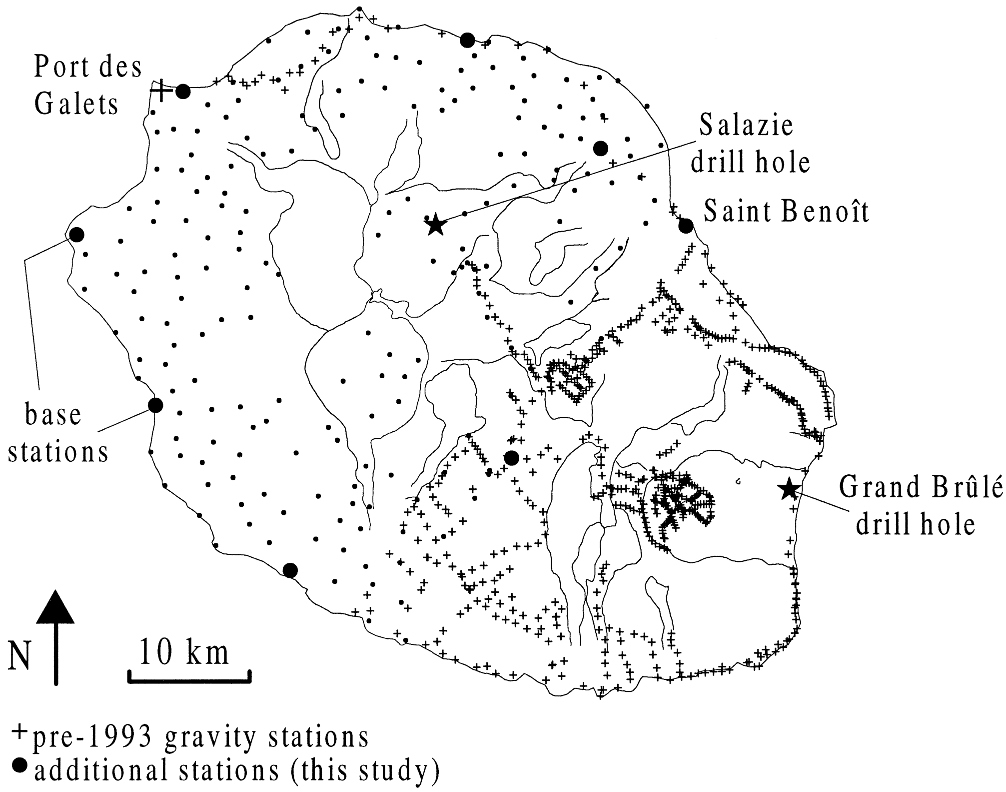

Fig. 2. Distribution of the available gravity data acquired on land before 1993 (crosses) and of the new gravity stations set up in 1993 on the western side of the island (full circles).

(Rançon et al., 1989), Cirque de Salazie (Demange et al., 1989).

The work of Lesquer (1990) shows that the most prominent anomalies on the island are two positive anomalies associated with intrusive complexes, one in the central area of Piton des Neiges and the other in the eastern part of Piton de la Fournaise (Grand Brûlé area). There is no similar anomaly in the summit area of Piton de la Fournaise although low amplitude and short wavelength anomalies can be attributed to preferential intrusive zones (Rousset et al., 1989).

4. The new gravity data

The distribution of available gravity stations on Réunion Island shows a critical lack of data on Piton des Neiges. The only available data were acquired on some roads either on the coast or going up the flanks of the volcano (Fig. 2).

In order to describe the structure of the island, we needed a more homogeneous data set. To achieve this, we carried out a regional survey on Piton des Neiges in June 1993 (Fig. 2). Two hundred and eighteen new stations were established with a spacing of about 2 km. Eight easily accessible stations were used as bases for drift corrections. Due to limited time and accessibility, some areas were not visited (Cirque de Mafate, some valleys and steeps-lope zones). Most stations were set up at geodetic benchmarks previously surveyed by the Institut Géographique National (IGN).

The processing steps leading to the Bouguer anomaly map are described in Appendix A.

5. Density estimates

Two deep geothermal exploration drill holes provided information about the in situ density distribution. They are located in Cirque de Salazie on Piton des Neiges and in the Grand Brûlé area (Fig. 2). From unpublished density measurements on samples from Grand Brûlé borehole and from unpublished information on density evolution with depth in the two sites, Demange et al. (1989) assume density values of 2.5 to 2.9×10^3 kg/m^3 for lava flows and pyroclastites and of 3.1 to 3.35×10^3 kg/m^3 for intrusive rocks.

Several methods, such as the Nettleton (1939) and the Parasnis (1962) methods, allow choice of a density for the near surface formations that minimises the correlation between the Bouguer anomaly and the topography. These methods are efficient if the

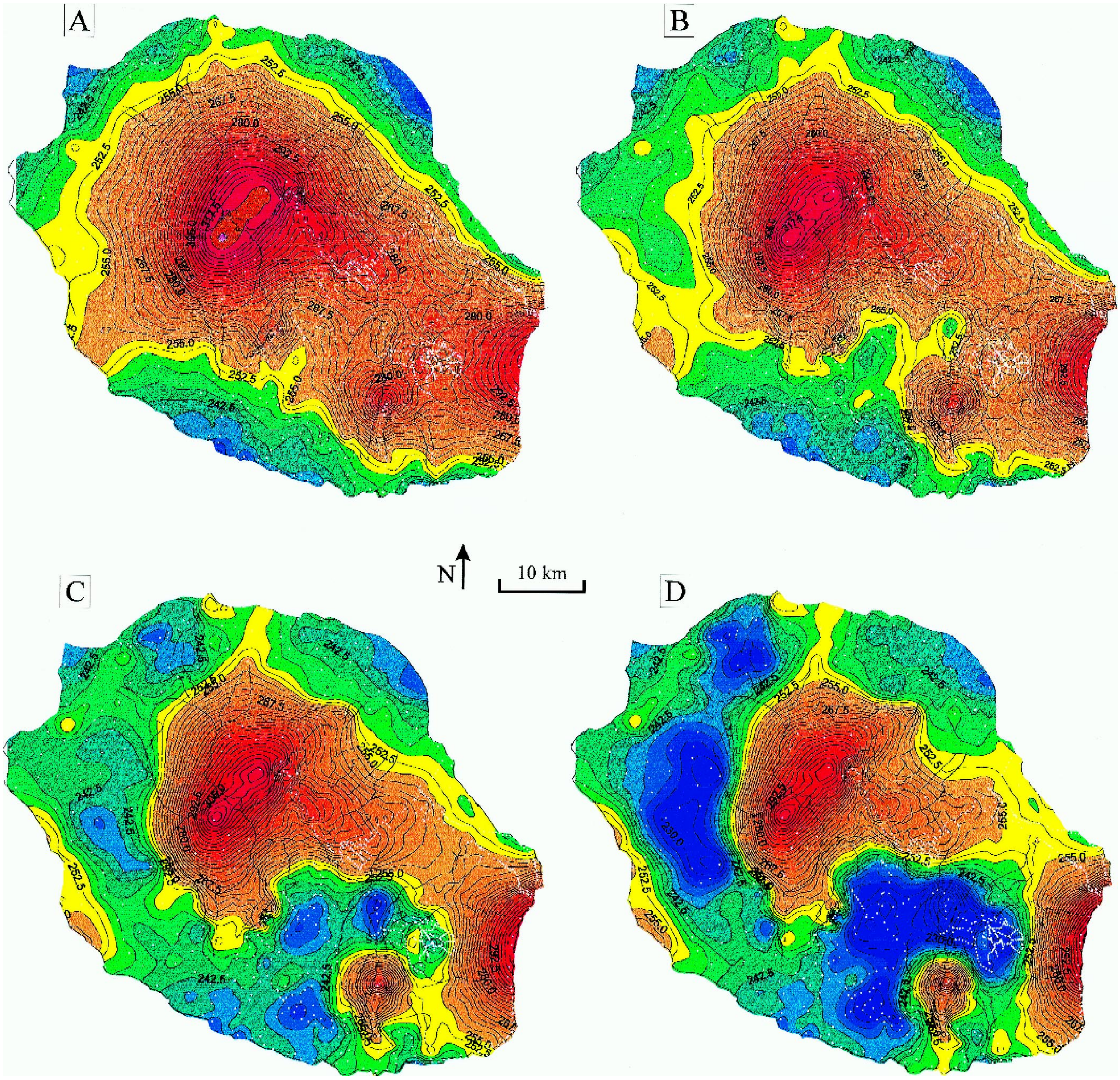

Fig. 3. Bouguer anomaly maps of Réunion Island computed with all available data. The density corrections are 2.5×10^3 kg/m^3 (A), 2.7×10^3 kg/m^3 (B), 2.9×10^3 kg/m^3 (C) and 3.1×10^3 kg/m^3 (D). Contour interval is 2.5 mGal.

density of the formations is homogeneous and if there is no natural correlation between the Bouguer anomalies and the topography. But, in volcanic terrains, Bouguer anomalies are often naturally related to topography because the highest areas correspond to the eruptive centres where denser rocks are emplaced at depth. Those features are well illustrated when tests using Nettleton's method are carried out in the case of Réunion. They clearly show that a single value of density cannot be chosen to process all the zones of the study. For this reason, we prefer to present Bouguer anomaly maps obtained for different correction densities because we think that they provide a better understanding of the density distribution than a single map would do.

Bouguer anomaly maps were thus computed for correction densities ranging from 1.9 to 3.1×10^3 kg/m^3 with a step of 0.2×10^3 kg/m^3. For the lowest values of density (1.9, 2.1 and 2.3×10^3 kg/m^3), the anomaly pattern remains too similar to the free air anomaly map, indicating that the value of correction density is too low. Conversely, a correction density of 3.1×10^3 kg/m^3 produces negative correlations between the topography and the anomalies in most areas, as it can be predicted from knowledge of the mean densities of volcanic rocks. The intermediate values of correction density (2.5, 2.7 and 2.9×10^3 kg/m^3) provide a distribution of anomalies that better outlines the gravity structure of the island. The maps were computed using a Krig-

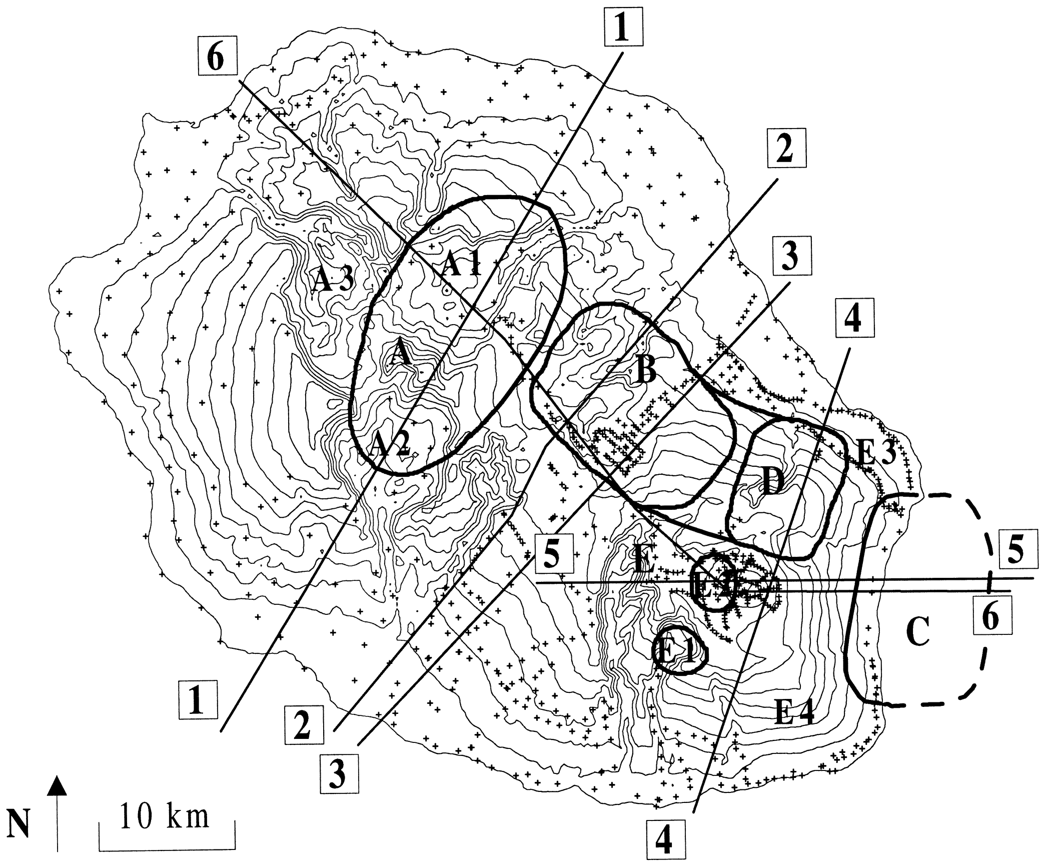

Fig. 4. Interpretative scheme of the distribution of Bouguer anomalies on Réunion Island, on a topographic base map of the island (contour interval: 250 m). Labels refer to dense structures described in the text. Their boundaries are based on visual interpretation of the Bouguer anomaly maps and on results from 2.5D models presented in the next figures (the six cross-sections are located on the map). Eastern boundaries of body C (dashed lines) are based on results from previous detailed gravity surveys conducted in the area (see text). Available gravity data are represented as crosses.

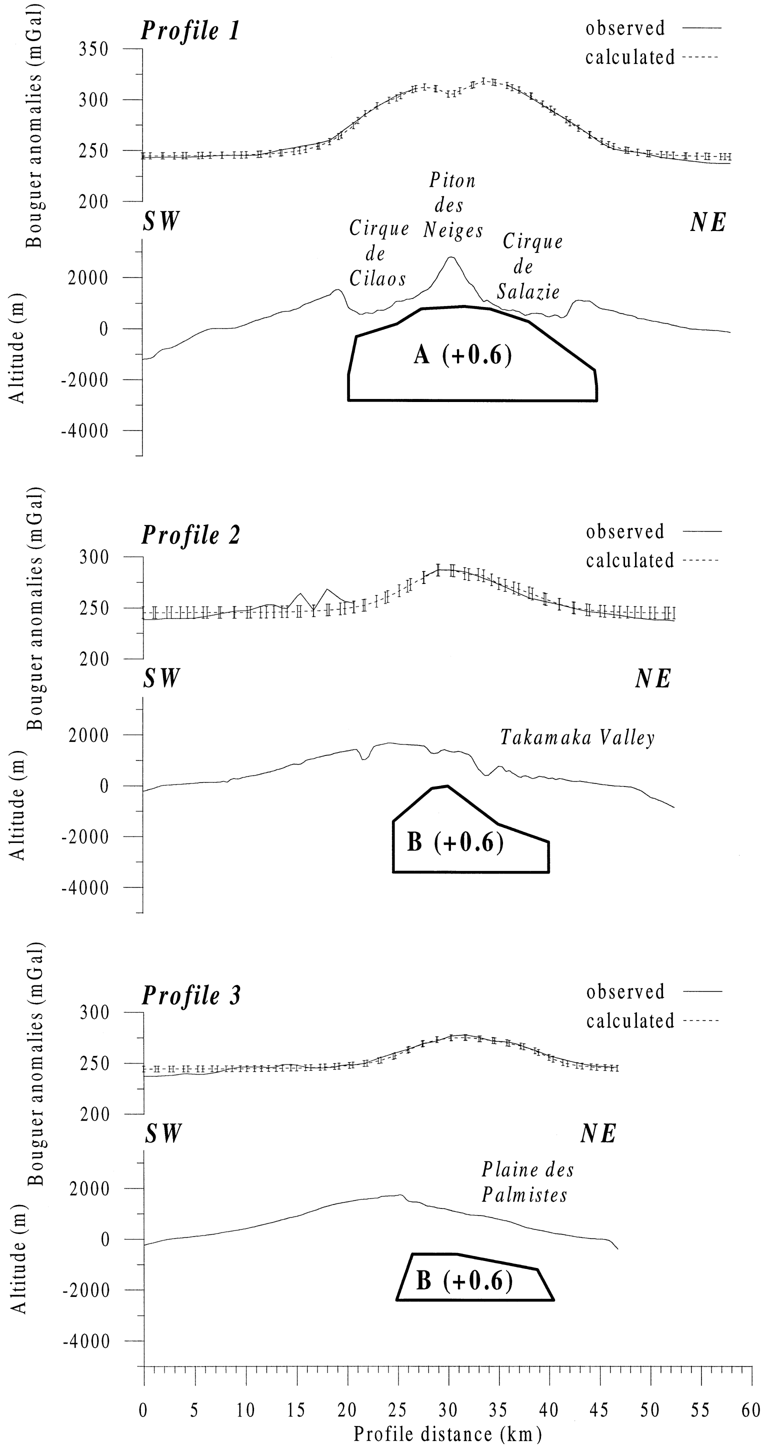

Fig. 5. 2.5D models on SW–NE profiles 1, 2 and 3 (shown in Fig. 4) on the western side of the island. The observed curve (gravity field obtained for a correction density of 2.7×10^3 kg/m^3) is drawn only in areas where data have been acquired. Density contrasts are in 10^3 kg/m^3 and errors on calculated gravity field are rms errors.

ging method with grid interval of 1 km. This interval respects the Shannon theorem, linking the density of measurements to the interval of interpolation, only in areas with a high density of stations in order to preserve information in these areas. In zones where the distribution of stations is less dense, interpretation is done carefully as small wavelength anomalies can be created.

Fig. 3 shows four maps for the Bouguer anomaly calculated with correction densities of 2.5, 2.7, 2.9 and 3.1×10^3 kg/m^3.

6. Interpretation of the Bouguer anomaly maps

The aim of this first interpretation of the new gravity map of Réunion Island is the characterisation of the main structures of the volcanic edifice. Our approach takes into account geological and geophysical knowledge of the area, as well as available quantitative interpretation of gravity studies in specific areas. Fig. 4 shows an interpretative scheme of the distribution of the main gravity structures of the island and the profiles along which some very simple models have been calculated. Using the semi-automatic program SAKI from the USGS, best fit 2.5D models were computed (Figs. 5–7). The Bouguer anomaly used for these models is the one obtained for a correction density of 2.7×10^3 kg/m^3. Without accurate information about parameters such as the density contrast between bodies and their surroundings, the vertical density gradient or the depth of the bodies, the models presented here cannot be considered as a representation of the true density distribution. However, they probably provide satisfactory indications for the depth and lateral extent of the dense bodies, whereas the base of the bodies is not so reliable. Despite a more homogeneous distribution of gravity data over the island, the density of data is still too small to allow 3D modelling or spectral analyses.

6.1. The main positive anomalies

Three main anomalies appear on every map shown in Fig. 3. They are located in the central area of Piton des Neiges, above the intrusive complex of Grand Brûlé, and on the eastern side of Piton des Neiges.

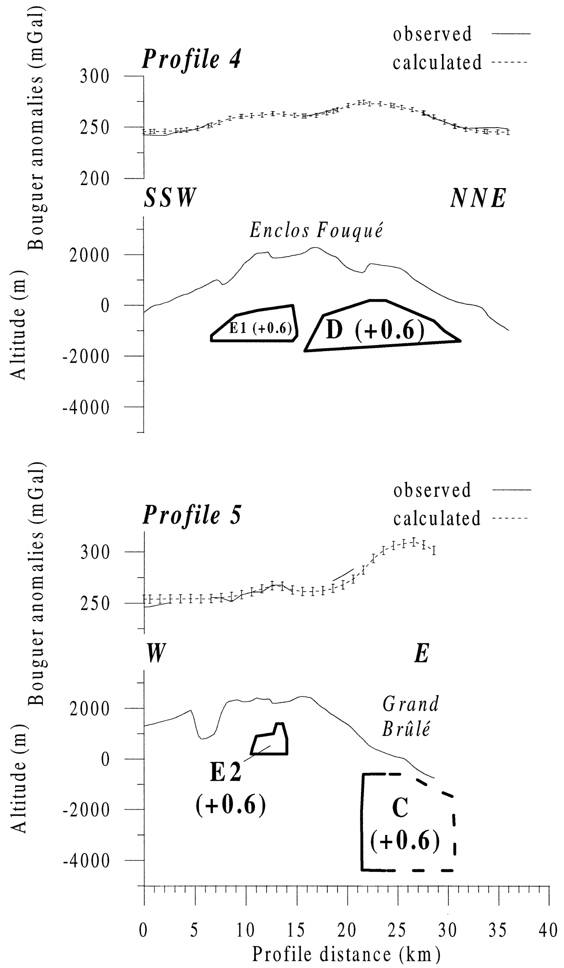

Fig. 6. 2.5D models on profiles 4 and 5 (shown in Fig. 4) on the eastern side of the island. The observed curve (gravity field obtained for a correction density of 2.7×10^3 kg/m^3) is drawn only in areas where data have been acquired. Density contrasts are in 10^3 kg/m^3 and errors on calculated gravity field are rms errors. Eastern boundaries of body C are drawn as dashed lines as they are based on results from previous detailed gravity surveys (see text).

6.1.1. The central zone of Piton des Neiges (anomaly A)

As previously shown by Lesquer (1990), this zone is characterised by an intense and broad positive anomaly. The maximums coincide with Cirque de Salazie (A1) and Cirque de Cilaos (A2) and form a NNE–SSW-elongated anomaly although this feature is not very well constrained due to the small number of measurements in the zone. Lack of data in Cirque

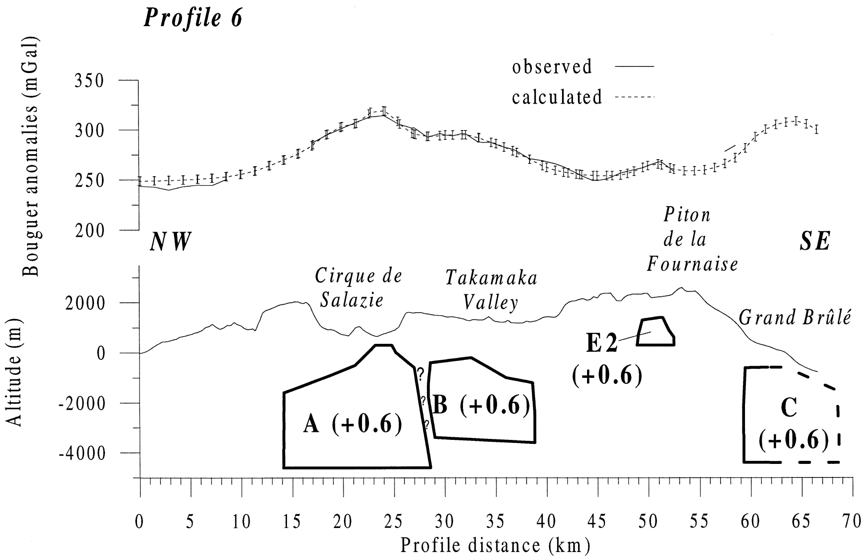

Fig. 7. 2.5D model on the NW–SE profile 6 shown in Fig. 4. The observed curve (gravity field obtained for a correction density of 2.7×10^3 kg/m^3) is drawn only in areas where data have been acquired. Density contrasts are in 10^3 kg/m^3 and errors on calculated gravity field are rms errors. Eastern boundaries of body C are drawn as dashed lines as they are based on results from previous detailed gravity surveys (see text).

de Mafate prevents knowing if a maximum also exists in this area (A3). However, a detailed gravity study carried out in Cirque de Salazie (Demange et al., 1989) shows a high gradient in the western part, suggesting that anomaly A does not extend significantly into Cirque de Mafate.

Although we suspect that anomaly A is amplified, because most stations were inside cirques (see Appendix B), it can be indisputably associated with the presence of dense rocks in the central part of Piton des Neiges where numerous sheet intrusions (dykes and sills) outcrop and, in some places, form more than 50% of the exposure (Rançon, 1982). Gabbroic complexes are also observed in valleys in Cirque de Salazie (Demange et al., 1989) and Cirque de Cilaos (Rançon et al., 1988) at an altitude of about 700 m. The geothermal drill hole in Cirque de Salazie (Demange et al., 1989) encountered a gabbroic complex from a depth of 1000 m below the surface to the bottom of the well (2000 m). According to a detailed gravity survey conducted at the same time, this complex is thought to be present in the southern half of the cirque and to deepen to the North. The density contrast between the intrusive rocks and the effusive and pyroclastic rocks ranges from 0.5 to 0.9×10^3 kg/m^3 (Demange et al., 1989).

The association of hypovolcanic bodies and swarms of sheet intrusions is a classic feature of the interior of oceanic shield volcanoes. Ryan (1987) has proposed that complexes of hypovolcanic (gabbro) intrusions and cumulates develop upwards during growth of a volcano. As a result, the centre of a mature volcano is characterised by a column-like body of high density rocks. The top of those complexes lies from about two to a few kilometres below the surface, and they can extend downwards to several kilometres, depending on factors such as the height of the volcano or the amplitude of the lithospheric deflection. Closer to the surface, swarms of sheet intrusions represent conduits for magma transport from the reservoirs to the surface or to shallow intrusions. The setting of this latter type of intrusion is well documented in active volcanoes, for example at Kilauea (Decker, 1987) or at Piton de la Fournaise (Lénat and Bachèlery, 1990). The main geological features observed in the central area of Piton des Neiges fit reasonably well this general model of the interior of an oceanic shield volcano. Assuming that, before erosion of the cirques, the volcano culminated at an altitude of about 3000 m, the top of the reservoir complex (e.g., the outcropping gabbros) would have been at an altitude of about 1000 m.

The presence of a large positive gravity anomaly in the central area of Piton des Neiges is in good agreement with such a model. Although the density of stations does not allow a precise 3D modelling of the anomaly, valuable constraints can be obtained from simple models. Profile 1 (Fig. 5) and profile 6 (Fig. 7) show the results of 2.5D models along SW–NE and NW–SE cross-sections running through anomaly A. The Bouguer anomaly used for these models is the one obtained for a correction density of 2.7×10^3 kg/m^3. A homogeneous density of 3.3×10^3 kg/m^3 has been assumed for the complex of intrusions and cumulates. This is probably an over-simplified representation of reality but it is sufficient to account for the depth and the horizontal extent of the dense body source and to show that it is deeply rooted. Indeed, even with a very large contrast of 0.6×10^3 kg/m^3, the models require the base of the dense body to be at several kilometres depth in order to induce the high amplitude of the observed anomaly. Our models agree with the simple model of Lesquer (1990) and with the local detailed results of Demange et al. (1989). It confirms the extent of the complex (20–25 km in length and 10–13 km in width).

The development of a complex of this size and with this vertical extent implies that Piton des Neiges was active for a long time. The zone beneath the present central area of Piton des Neiges must have remained a stable locus of volcanic activity, probably for a considerable period of time before the volcano emerged, so that a column of intrusions and cumulates could reach a height of several kilometres while the volcano was growing.

6.1.2. The area to the east of Piton des Neiges (anomaly B) and its possible connection with anomaly D

A prominent positive anomaly (B) appears east of Cirque de Salazie and merges with anomaly A. This strong anomaly, which was also shown on the map of Lesquer (1990), has a maximum in Takamaka Valley but this could be influenced by the low elevation of the stations in the valley (see Appendix B). Although no geological data are presently available to identify the nature of this dense body, the interpretation of aeromagnetic data (Malengreau, 1995; Lénat et al., in revision) strongly suggests the presence of an old (inversely magnetised) volcanic centre.

We specified the geometry of the body from the 2.5D models along profiles 2, 3 and 6 (Figs. 5–7). We assumed a density of 3.3×10^3 kg/m^3 for the dense rocks, which is similar to the inferred density of anomaly A. According to the models, the top of the body lies below sea level (between 0 and 1 km) and has a vertical extent of several kilometres. This vertical extent is larger on profile 2 (to the west, in Takamaka Valley) than on profile 3 (to the east, in Plaine des Palmistes). In a NE–SW direction, it is about 15 km wide.

A possible connection between anomalies A and B is more difficult to assess. The models (Figs. 5 and 7) only show that the tops of the respective body sources are at significantly different depths: top of body A some hundred meters above see level and top of body B some hundred meters below see level. Top of body A on profile 6 (Fig. 7) deepens to the North, as already shown in a detailed gravity survey conducted in Cirque de Salazie (Demange et al., 1989). Assuming the same density for the two bodies, the one of anomaly B is also less rooted than the one of anomaly A. It can thus be inferred that the two bodies are distinct even if partly coalescent.

Anomaly B seems to be part of a positive gravity ridge extending towards the SE to anomaly D (Fig. 3). Unfortunately, data are scarce on the Northeast and North flanks of Piton de la Fournaise and this part of the inferred ridge is not well defined. Profile 4, across Piton de la Fournaise, runs through anomaly D (Figs. 4 and 6). Although the data are discontinuous, a dense body can be defined to account for the extrapolated anomaly. The top of this body would lie at a similar depth to the one of anomaly B on profiles 2 and 3. If the same density of 3.3×10^3 kg/m^3 is assumed, the inferred body would have a smaller vertical extent but spread over a similar area along the profile.

The gravity ridge formed by anomalies B and D corresponds to dense bodies that are unknown at the surface and which have not been penetrated by drilling. It is therefore likely that they correspond to ancient structures overlaid by subsequent formations. The ridge also coincides with a buried massif of old (inversely magnetised) rocks (Malengreau, 1995; Lénat et al., in revision) and a seismic tomography (Charvis et al., submitted; Gallart et al., submitted) has confirmed the presence of a high velocity axis in the same area. The gravity ridge is definitely not an axis joining the centre of the present subaerial volcanoes Piton des Neiges and Piton de la Fournaise. In Fig. 3, the axis of the gravity ridge is clearly displaced towards the North.

As it has been explained above for the interpretation of anomaly A, high density bodies in this volcanic context correspond to intrusions, hypovolcanic massif and cumulates. We are therefore led to conclude that bodies B and D are the remains of ancient volcanic centres. We have named this ancient edifice Takamaka Volcano after the area where the intensity of the gravity anomaly is the highest. Whether or not anomaly D is a distinct structure or the continuation of anomaly B cannot be unambiguously established with the present data set.

6.1.3. The anomaly of the Grand Brûlé complex (anomaly C)

This anomaly is well known from several previous detailed gravity surveys carried out in this area (Rançon et al., 1987, 1989; Rousset et al., 1987, 1989; Rançon, 1990). It is clearly associated with a gabbroic and cumulate complex that has been encountered by a deep geothermal exploration drill hole from a depth of 1000 m down to the bottom of the well at 3000 m. In plan view, it is elongated in a N–S direction (12–15 km). Laterally, the anomaly is less well defined. An offshore study by Rousset et al. (1987) shows that it does not extend significantly towards the east. Onshore, the data are almost restricted to the coast but the shape of the anomaly tends to indicate that the western boundary is only a few kilometres away from the coast. This dense body must have a vertical extent of several kilometres to account for the high intensity of the anomaly.

As explained previously (anomaly A), in the context of a basaltic shield volcano, such structures represent the magmatic reservoir complexes of volcanic centres (Ryan, 1987). The Grand Brûlé complex has been an enigma for a long time since no volcanic centre had ever been recognised in this area. The discovery of remains of an ancient edifice underlying Piton de la Fournaise has recently provided an explanation for this structure. Indeed, the study of the offshore area to the east of Piton de la Fournaise (Lénat et al., 1990; Labazuy, 1991) and the interpretation of airborne and marine magnetic data (Malengreau, 1995; Lénat et al., in revision) have shown that rocks older than 0.78 Ma (i.e., older than the last geomagnetic reversal) are present beneath the significantly younger Piton de la Fournaise. All these interpretations lead us to propose that the Grand Brûlé complex belongs to an ancient volcanic centre that we have named Alizés Volcano (Fig. 1).

6.2. Piton de la Fournaise anomalies (E)

The gravimetric signature of Piton de la Fournaise is very different from that of Piton des Neiges. The main difference is that Piton de la Fournaise lacks a strong positive anomaly that is present in other areas and indicates the presence of a dense root. Nevertheless, some small more or less distinct positive anomalies can be recognised and we have annotated them as E (Fig. 4).

Anomaly E1 has a marked maximum in Rivière Langevin. Profile 4 runs on the eastern side of this anomaly (Fig. 6). On the section, it can be modelled by a 1 km thick body with a roof between 0 and 1 km below sea level. The location of the maximum in Rivière Langevin can be easily explained if we note that the measurements are taken at the bottom of the valley, 1500 to 2000 m lower than the measurements just to the North. The relationship is illustrated in Appendix B.

Anomaly E2 is located a few kilometres to the west of the present summit of Piton de la Fournaise. On profile 5 (Fig. 6), this structure is modelled by a body (with a density of 3.3×10^3 kg/m^3) whose top is located significantly above sea level. Modelling by inversion methods by Rousset et al. (1989) also argue for a shallow origin of this anomaly. This anomaly coincides with the previous central area of Piton de la Fournaise before it migrated eastwards about 0.15 Ma ago (Bachèlery and Mairine, 1990; Bachèlery and Lénat, 1993). The gravity anomaly might be explained by the presence of a small intrusive complex beneath this ancient centre of Piton de la Fournaise. Evidence supporting our interpretation also comes from the frequent presence of gabbro and cumulate enclaves in the eruptives of the area (Bachèlery, 1981).

In contrast, the presently active centre of Piton de la Fournaise does not show a marked positive anomaly that would indicate the presence of an intrusive complex. A seismic tomography survey of the central area (Nercessian et al., 1996) suggests that a column of higher velocity (hence, of higher density) exists beneath the summit craters. Rousset et al. (1989) also show that weak relative positive gravity anomalies in the summit area reflect the presence of shallow intrusions.

Anomalies E3 and E4 designate the present NE and SE rift zones of Piton de la Fournaise. These structures should contain a high proportion of dykes that would induce positive gravity anomalies, but unfortunately the present data set does not allow conclusive interpretations.

7. Discussion and conclusions

The new gravity map of Réunion allows study of the main dense structures of this large and long-lived volcanic system. Our study is focused on the interpretation of the positive anomalies that indicate the presence of intrusive and cumulate complexes underlying the active areas.

Two very large complexes can be unambiguously identified: beneath Piton des Neiges (anomaly A) and beneath the Grand Brûlé area (anomaly C).

Piton des Neiges complex, where exposed, consists of swarms of sills and gabbro stocks. This complex has also been encountered by a deep geothermal drill hole in Cirque de Salazie. The result inferred by the gravity study is the large lateral and vertical extent of the complex. Following the work of Ryan (1987), the large vertical dimension of the complex shows that growth of Piton des Neiges started in the early stages of Réunion volcanism and that the intrusive and cumulate complex developed upwards while the volcano was becoming larger and higher. The horizontal extent of the complex is significantly larger than the usual size of collapse calderas in oceanic basaltic shields (Gudmundsson, 1988; Gudmundsson et al., 1997). Indeed, in such a context, it is generally admitted that the collapse dimension does not exceed that of the reservoir although it is also related to the depth of pressure sources. If this is the case, the size and the elongated shape of Piton des Neiges complex might suggest migration of the volcanic centres.

The same interpretation can be made for the anomaly of the Grand Brûlé complex. The main interest of this structure is that it is not associated with the present-day subaerial or submarine edifice. Therefore, the complex reveals the existence of a major ancient volcanic centre in this part of the island, similar in importance to Piton des Neiges. Magnetic (Malengreau, 1995) and bathymetric work (Lénat et al., 1990) show that Piton de la Fournaise was built on the remains of an ancient volcano. We have named this volcanic centre Alizés Volcano.

Anomalies B (Takamaka) and D (northern flank of Piton de la Fournaise) suggest the presence of a ridge of dense rocks culminating between 0 and 1 km below sea level. No geological evidence can be found to provide information of the nature of these dense rocks. We can only propose an interpretation by analogy with the other well-identified dense structures. The ridge also coincides with structures detected by magnetic and seismic work and is not aligned with the present axis joining the summits of Piton des Neiges and Piton de la Fournaise. We suggest that these anomalies are caused by the presence of intrusive and cumulate complexes associated with an ancient volcanic centre that we have named Takamaka Volcano. Questions remain, however, about a possible connection between anomalies A and B and between anomalies B and D.

The gravity signature of Piton de la Fournaise contrasts with that of all previously described Réunion Island structures. The main difference is that no large dense complex exists beneath Piton de la Fournaise. A reasonable explanation is that Piton de la Fournaise is a young volcano that has not yet developed such complexes. However, low positive anomalies indicate the presence of some dense rocks as it is the case in the western part of the edifice (Plaine des Remparts and Plaine des Sables) where enclaves of gabbro and cumulates in lavas are considered samples of underlying dense complexes. A recent (0.15 Ma) eastward migration of the centre of activity of Piton de la Fournaise accounts for the lack of a large positive anomaly beneath the active craters.

The new gravity map of Réunion contributes to the knowledge of the structure and evolution of this hot spot volcanic system. A new model is progressively being built. This new model must take account of the long term activity of Piton des Neiges, and Takamaka and Alizés volcanoes as major centres of activity in the past. Piton de la Fournaise appears to be a young volcano growing on the remains of the two older volcanoes.

More measurements onshore and offshore are essential for a better definition of the gravity structures of the edifice.

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Appendix A. Data processing

Gravity data were acquired with a LaCoste and Romberg gravity meter (model G). The accuracy of the measurement is about 0.01 mGal. Two hundred and eighteen new stations were measured. Eight easily accessible stations were used as bases for instrumental drift corrections (Fig. 2).

Our stations were set up at sites previously surveyed by the Institut Géographique National (IGN). Most of them are geodetic benchmarks recently surveyed with the Global Positioning System (GPS). Their latitude and longitude are given with a precision of 1 cm to 1 mm and their height with a precision of 1 cm to 10 cm. The other sites are spot heights located on the 1/25,000th topographic maps. Their height is assumed to have a precision of 1 m to 5 m at most (C. Luzet, IGN, personal communication). Horizontal coordinates of these stations were obtained by digitisation on 1/25,000th topographic maps with an inferred precision of about 50 m.

Calibrated data were corrected from earth tides using the algorithm of Longman (1959). Calculated drift is about 0.003 mGal, in a range between 0.095 and −0.078 mGal.

All the data were tied, in the IGSN71 system, to the international base station located at the church of Saint Benoît (Fig. 2) where absolute gravity is 978,926.66 mGal.

For the plateau correction, we used the formula for a slab following the sphericity of the earth (LaFehr, 1991) and extending to 167 km away from the station.

For the terrain corrections, we used the Hammer's subdivision of the space surrounding the station in sectors. In order to get a better estimation of the difference in altitude between a sector and the station, we used Digital Elevation Models (DEMs) to calculate a plan averaging the topography in each sector (Olivier and Simard, 1981). Because we had three DEMs with their own precision and due to calculation limits, we used different grid intervals for different Hammer zones. For the inner zones (to 2.614 km away from the station), the DEM has a grid interval of 40 m; for the intermediate zones (2.614 km to 22 km), the grid interval is 250 m and it is 500 m for the outer zones. We calculated the terrain corrections to 57 km away from each station. This distance corresponds to the maximum extension of the DEM from a gravity station on the coast. Even if terrain corrections in outer zones are non zero, they can be considered as negligible in comparison with the topographic effect of areas close to the stations. Because of the rough relief of Réunion Island, the terrain correction can be very important. Using a correction density of 1.9×10^3 kg/m^3, the terrain correction varies from 4 to 30 mGal and from 7 to 50 mGal for a correction density of 3.1×10^3 kg/m^3.

Estimation of the accuracy of the gravity anomalies includes the estimation of the precision of the measurements and the estimation of the errors in the calculation of the anomalies. According to the formula used to calculate the Bouguer anomaly, the mean quadratic error in the Bouguer anomaly is given by:

$$E\_AB = \left[(E\_g_{obs})^2 + (E\_g_{phi})^2 + (E\_FAC)^2 + (E\_BC)^2 + (E\_TC)^2 \right]^{1/2}$$

where E_g_{obs} is the measuring precision, E_g_{phi} the error in latitude correction, E_FAC the error in altitude correction, E_BC the error in plateau correction and E_TC the error in terrain correction.

Reoccupation of some stations gives a measuring precision of the order of 0.1 mGal (E_g_{obs}).

A maximal error of 50 m in latitude leads to an error in latitude correction of about 0.05 mGal (E_g_{phi}). Accuracy of height of our stations is of 5 m at most. This means that error in altitude correction (E_FAC) is about 1.5 mGal and error in plateau correction (E_BC) is about 1/10,000th mGal for a correction density of 1.9×10^3 kg/m^3 and 1/1000th mGal for a correction density of 3.1×10^3 kg/m^3.

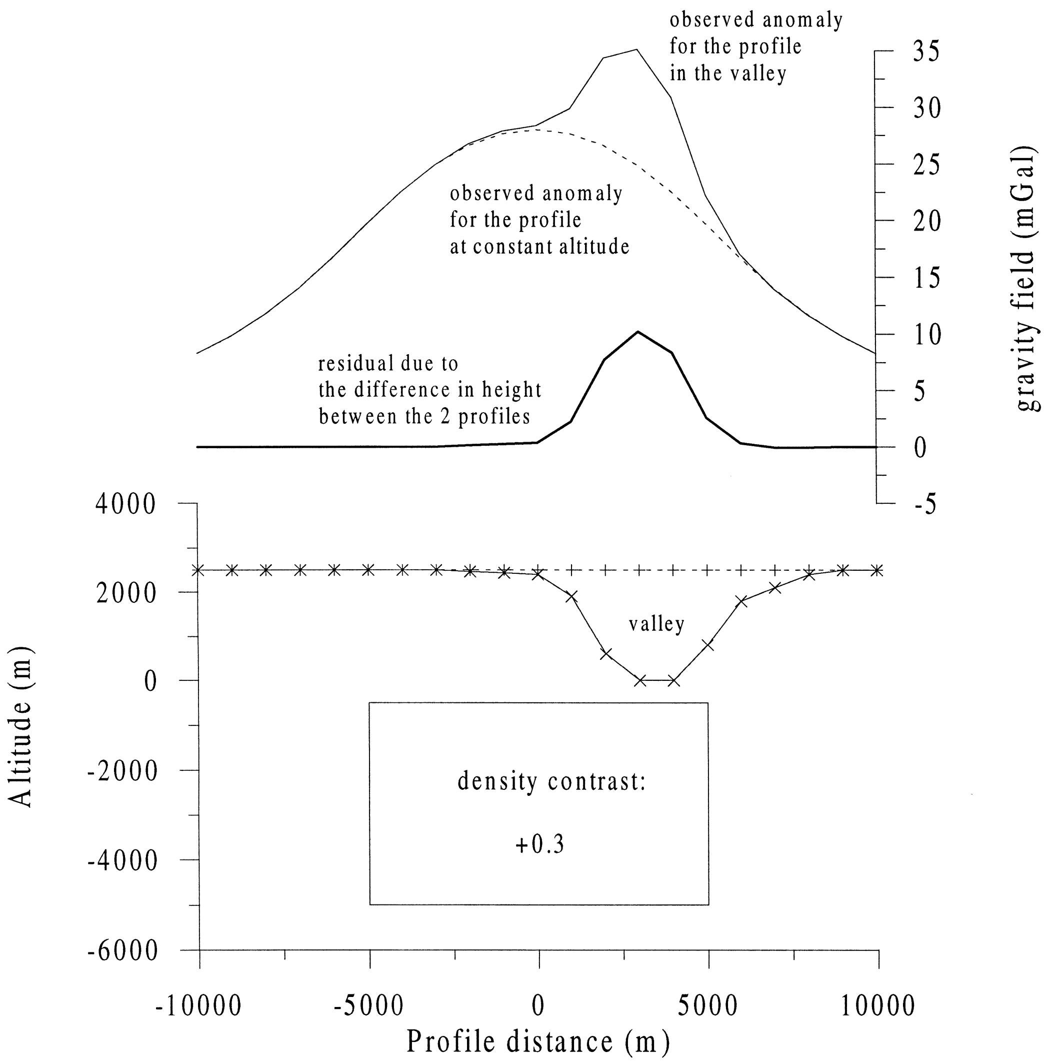

Fig. 8. Theoretical model showing the relation between the anomaly pattern and the variable height of gravity stations when a density contrast exists at shallow depth.

Estimation of terrain correction depends on the correction density but also on the accuracy of DEM. An uncertainty of 25% can be a realistic estimation (Froger, 1990). As our terrain correction with a correction density of 3.1×10^3 kg/m^3 is about 15 mGal, we estimate the error of the terrain correction of 4 mGal (E_TC).

Most of the components of uncertainty in the estimation of the accuracy of Bouguer anomalies are negligible in comparison with the terrain correction component. The final accuracy of the Bouguer anomaly is estimated at ± 4 mGal.

Appendix B. Relief effects

The intensity and the contours of gravity anomalies are related to the geometry and depth of the body sources. The gravity signal increases as the measurements are taken closer to them; the increase is not linear and is inversely related to the distance.

When gravity stations are located over a relief with large variations of altitude, the shape of the anomaly may be greatly influenced. The theoretical example of Fig. 8 illustrates the relation between the anomaly pattern and the variable height of gravity stations when a density contrast exists at shallow depth.

On Réunion, these effects can be significant. For example, the anomalous dense body of Piton des Neiges is very shallow at the bottom of Cirque de Salazie and Cirque de Cilaos. Whether a measure is taken at the bottom of the cirques or at the top of their rims will give different values of anomaly for two gravity stations close to each other in plan view.

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