Gravimetric structure and growth history of the volcanic seamounts of the Vitória-Trindade Chain, State of Espírito Santo, Brazil, based on the satellite-derived data

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Abstract

This paper reports gravimetric structure and growth history of the volcanic seamounts of Vitória Vitória-Trindade chain, State of Espírito Santo, Brazil, based satellite-derived data. The seamounts have about 30 km in base diameter, 10 km in flat-top diameter, and 4000 m in relative height. The flat-tops are constant in depth without evidence of basement subsidence. The size and frequency of the volcanoes become smaller from west to east. The western half of the chain shows basement uplift with a relative height of 2000. The small seamounts have Bouguer anomaly about 100 mGal lower than the adjacent and their weight is sustained mainly by mechanical firmness of the basement. The large volcanoes show ring-like Bouguer structure with central high and marginal low. The marginal low is about 100 mGal lower than the adjacent abyssal plane and the central high is about 80 mGal higher than marginal low. The central high is attributed to the radial dykes around the central conduit. The seamount weight is supported mainly by mechanical firmness and partially by isostatic compensation of crustal down-buckling. Very large volcanoes have bull's eye-like low Bouguer spots along the marginal low, attributed possibly to lateral cones buried by sedimentary deposits. The mountain foot has Bouguer anomaly 20 to 40 mGal higher than the adjacent areas, called the peripheral high. It is due to the rebound of the crustal down-buckling by seamount weight. The regional Bouguer anomaly suggests lithosphere thinning along the volcanic chain which becomes weak from west to east.

Introduction

The Vitória-Trindade Chain is a E-W trend magmatic alignment with 950 km of total length along the latitude 20°40'S in the State of Espírito Santo, Brazil (Figure 1). There are 19 large volcanoes and many small ones. Two highest volcanoes form Trindade Island and Martim Vaz Island, which have more than 5000 m of relative height.

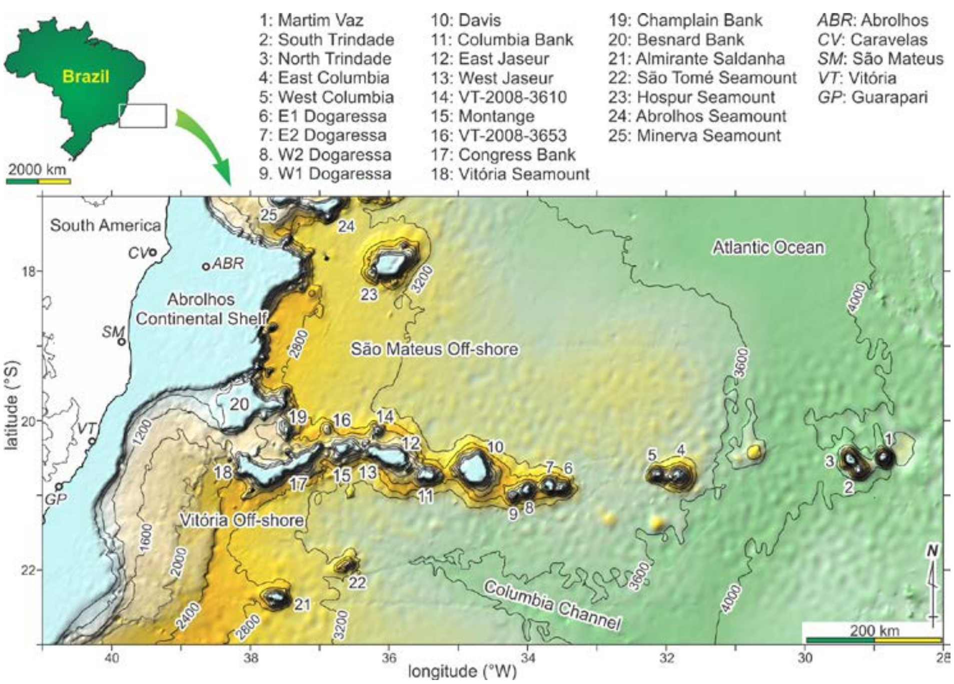

Figure 1. Bathymetric map for the Vitória-Trindade Chain, State of Espírito Santo, Brazil, based on the TOPEX ver. 15.1, modified form Motoki et al. (2012).

These islands expose strongly silica-undersaturated ultrabasic rocks with OIB-like isotopic ratios, such as basanite and nephelinite. Most of the K-Ar datings for the Trindade Island samples range from 2.0 to 3.0 Ma

(Cordani, 1970; Valencio & Mendía, 1974). Some of the samples of the Martim Vaz Island are still younger. Recent studies based on the dredge samples revealed that the Columbia Seamount, Dogaressa Bank, Davis Bank, and Jaseur Bank are made up mainly of alkaline picrite and ankaramite (Skolotnev et al., 2010). Two U-Pb datings for the Jaseur Bank show concordant ages of 29.8 Ma (Skolotnev et al., 2011).

The volcanic seamounts generally have conical form with representative base diameter of 30 km, flat-top diameter of 10 km, and relative height of 4000 m. The western half of the chain shows notable plateau-like morphologic elevation with a relative height of 2000 m.

The authors show gravimetric structure and growth history of the volcanic seamounts based on TOPEX ver. 15.1 and Gravity Anomaly ver. 20.

Research methods

The TOPEX ver. 14.1 has apparent horizontal resolution of 0.9 km. The resolution is estimated to be about 5 km. The Gravity Anomaly ver. 20 has 1.85 km of apparent resolution and its estimated real resolution is 4.5 km. The Bouguer anomaly has been calculated with the help of the original software Schwelt ver. 1.0, adopting the crust density of 2.65 g/cm, sea water density of 1.03 g/cm, and gravity constant is 6.67259×10^{-11} m^3/s^2kg.

Ocean bottom morphology

The volcanic chain has an inflection at its central part, about 34°W. The eastern half has N85°E trend and western half, N77°W. The flat-tops of the seamounts are constant in depth, about 50 m and no basement subsidence is observed. The high volcanic edifices, such as the Vitória Island (2) and Martim Vaz Island (1), have steep slope, of about 25°, and low volcanoes, as the VT-2123-3207, has gentle slope of 5°. The former is constituted by lava flows and the latter, by unconsolidated pyroclastic deposits. Most of them are minor than 30 km in base diameter. The Davis Bank (10), Vitória-Congress composite seamount (18), and Jaseur Bank (12) are exceptional.

The Figure 2 presents base level map (*sekkokumen*) with grid interval of 27.8 km, which eliminates virtually the morphologic elevations of volcanic seamounts, showing basement relieves. This map visualises submarine highlands along the volcanic chain originated from the basement uplift of about 2000 m, proposed by Skolotnev et al. (2010). At relative height becomes lower from west to east, varying 2000 m to 1000 m.

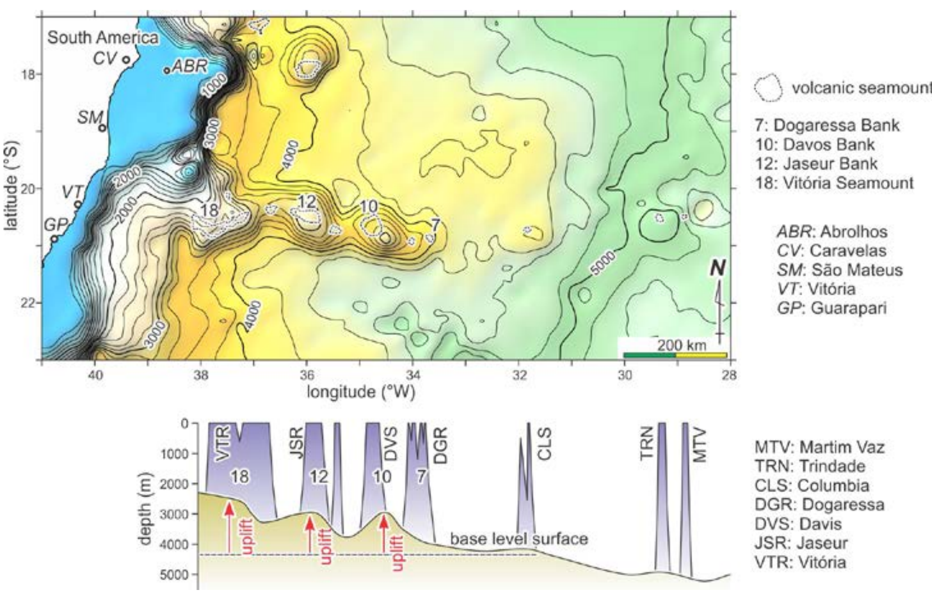

Figure 2.
Base level map of the grid interval of 27.8 km for the studied area. The abbreviations are same of the Figure 1.

Free-air anomaly

The Figure 3 presents free-air anomaly map for the studied area. The free-ar of the abyssal plane is constant, ranging from -20 to 0 mGal, suggesting almost full isostatic equilibrium. On the other hand, the continental shelf shows gradual elevation of free-air from coast to continental shelf break, from -10 mGal to 60 mGal.

The São Mateus off-shore has continental shelf exceptionally large, being about 200 km wide, called the Abrolhos Continental Platform. The free-air increases from the coast line to the continental shelf break, ranging from -10 mGal to 135 mGal. This phenomenon is attributed to continental crust thinning toward oceanic side. The total crustal thinning is 2 km for the Vitória off-shore and 5 km for the São Mateus off-shore. Based on the geomorphologic and gravimetric contrasts, the Vitória off-shore is called SP-type (São Paulo type), and São Mateus off-shore, ES-type (Espírito Santo type).

The pelagic abyssal plane of São Mateus off-shore has free-air about 15 mGal higher than the adjacent areas (Figure 3, SMT-AP) and that of the Vitória off-shore (VTR-AP), about 10 mGal higher. The zone between them, along the Vitória-Trindade Chain, has free-air 30 to 40 mGal lower than the adjacent areas.

The Figure 4 presents relationships between gravimetric anomalies and depth, so-called gravimetric interpretation diagrams. In shallow depth, the continental shelf (SH) and the seamount flat-top (GY) constitute two distinct groups, respectively of -20 to 100 mGal and 100 to 280 mGal. The seamount slopes show a positive correlation on this diagram, indicating that the seamounts are sustained mainly by mechanical firmness of the basement without isostatic compensation. The continental slope (SL) also is supported by the basement firmness.

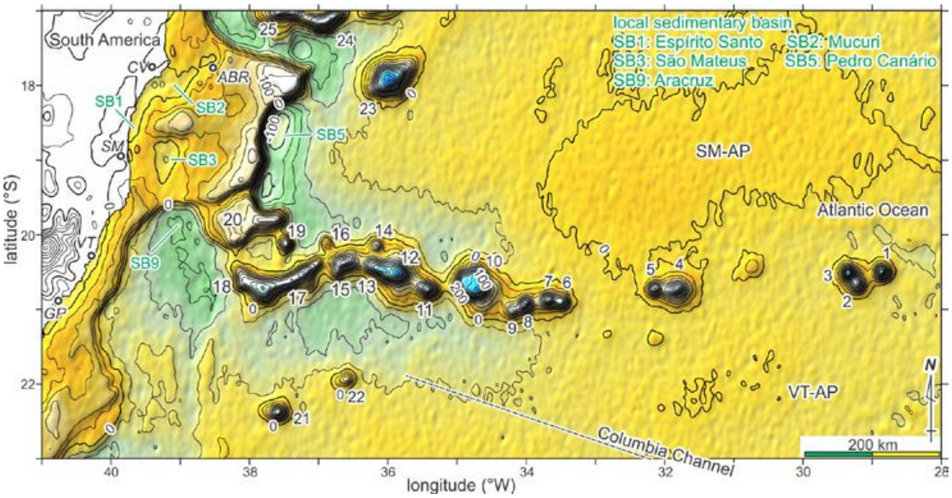

Figure 3.
Free-air anomaly map in mGal for the Vitória-Trindade Chain and the adjacent areas based on the TOPEX ver 14.1. Names of the local sedimentary basins (SB1~SB9) are proposed by the present paper.

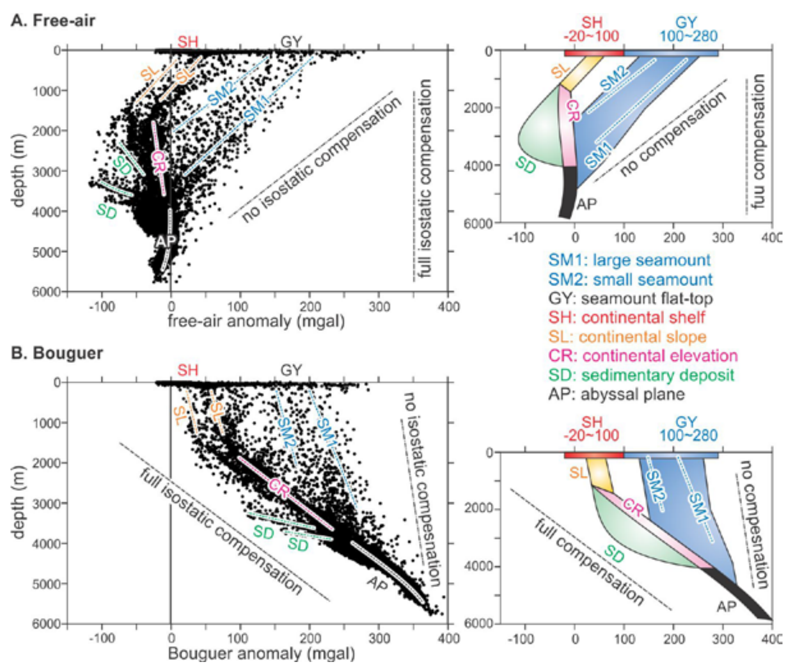

Figure 4.
Relation between gravimetric anomalies and depth for the Vitória-Trindade Chain, western Equatorial Atlantic Ocean: A) Free-air anomaly; B) Bouguer anomaly.

The abyssal plane (AP) shows full isostatic compensation (Figure 6A). Some parts of the continental rise (CR) show partial isostatic compensation. There are the domains with abnormally low free-air anomaly (SD), which is 90 to 130 mGal lower than the adjacent continental slope. They are attributed to the thick layer of sedimentary deposit.

Bouguer anomaly

The Figure 5 presents Bouguer anomaly map. The continental shelf shows gradual Bouguer increase from coast to continental shelf break. The sedimentary basins on the continental shelf (SB1, SB2, SB3) have Bouguer anomaly about 50 mGal lower than the adjacent area. The Bouguer characteristics on the continental shelf follow the free-air ones, indicating that the basement depression of the sedimentary basins is sustained by mechanical firmness of the basement, without isostatic compensation.

Different form the free-air anomaly, the continental slope shows gradual Bouguer elevation from continental to oceanic sides, without sudden jump. In the SP-type passive margin of Vitória off-shore, the Bouguer elevation rate is about 0.5 mGal/km and in the ES-type margin of São Mateus off-shore, about 2 mGal/km. The sedimentary basins on the continental rise, as SB5 and SB9, show no notable Bouguer depression in spite of the strong free-air depressions.

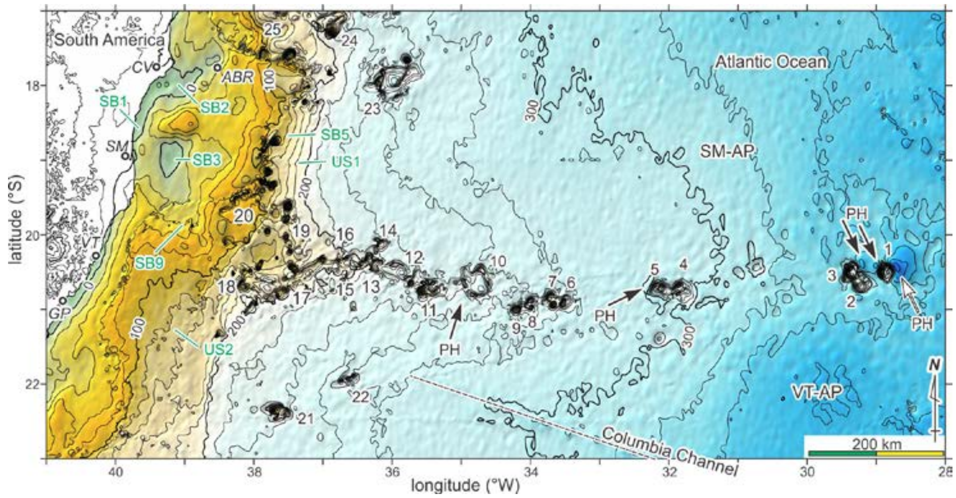

Figure 5. Bouguer anomaly map for the Vitória-Trindade Chain and the adjacent areas based on the satellite data of the TOPEX ver 1.4.1. The US1 and US2 represent Bouguer upslope from continental to oceanic side. The other abbreviations are the same of the Figure 3.

Along the Vitória-Trindade Chain, regional Bouguer anomaly is lower than the adjacent areas, forming wide and a shallow gutter-like east-west trend linear depression. The Figure 6 shows summit level map (*seppômen*) of the Bouguer anomaly with grid interval of 14 km, which eliminates virtually the local Bouguer depressions due to the volcanic seamounts. The low Bouguer zone is 50 mGal in maximum depth at the western corner, but the depth decreases to east. For example, at 37°30'W, close to the Congress Bank (17), the Bouguer depth and slope angle are respectively 50 mGal and 0.27 mGal/km, and at 30°00'W, close to the Trindade Island (3), they are respectively, 8 mGal and 0.02 mGal/km.

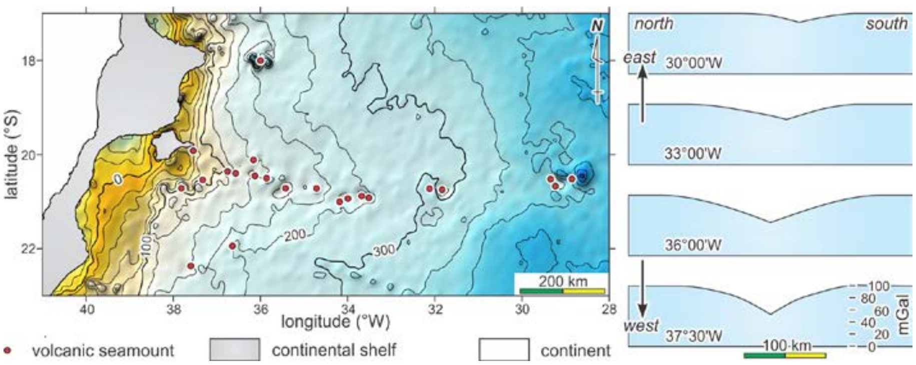

Figure 6.
Bouguer anomaly summit level map based on the grid interval of 14 km and their north-south cross sections.

The seamounts have Bouguer anomaly 60 to 140 mGal lower than the surrounding area. The small ones have simple funnel-shaped Bouguer depression. Those larger than 30 km in base diameter have a local Bouguer high at the central part of the volcanoes constituting a ring-like Bouguer structure composed of central high (CH) and the marginal low (ML). The central high is 60 to 100 mGal higher than the marginal low and the top is of the same level or little lower than the abyssal plane.

In cases of the very large volcanoes, for example the Davis Bank (10), there are some bull's eye-like funnel-shaped local Bouguer low spots along the marginal low ring, suggesting that the central volcano is surrounded by small lateral cones which are buried by sedimentary deposits. The Davis Bank has two central highs indicating tow magma feeder (10A, 10B, Figure 7B).

Some seamounts have peripheral zones where Bouguer anomaly is about 20 to 40 mGal higher than the abyssal plane (Figure 7, arrows, PH), called peripheral high. They are about 20 km x 40 km of horizontal extension. The peripheral high at the eastern foothill of the Martim Vaz (Figure 5, open arrow) is exceptionally large, with 70 km x 50 km of extension and maximum relative anomaly of 70 mGal (Figure 7A).

The diagram of Bouguer anomaly vs. depth shows high-angle negative trend for the seamount slope (Figure 4B, SM1, SM2). These trends indicate that the seamount weight is sustained mainly by mechanical firmness of the basement and partially by isostatic equilibrium. For the small seamounts about 95% of the seamount weight is supported by mechanical firmness.

Structure of the volcanic seamounts

The Bouguer anomaly of the seamounts is generally lower than the surrounding abyssal plane. It is explained by the following hypothesis: A) Low -density constituent materials; B) Oceanic crust down-buckling of; C) Deep volcano root of basaltic composition.

The hypothesis A can explain the local Bouguer low of small seamounts. Supposing average density of the pillow lava as 2.6, the total thickness of the lava should be 6 km. It is larger than the seamount height. Therefore, in order to justify the Bouguer depression, only less than 1 km of the crustal down-buckling is enough (Figure 8A). For larger seamounts, larger volcano root is necessary. In these cases, the hypothesis B and C become more important.

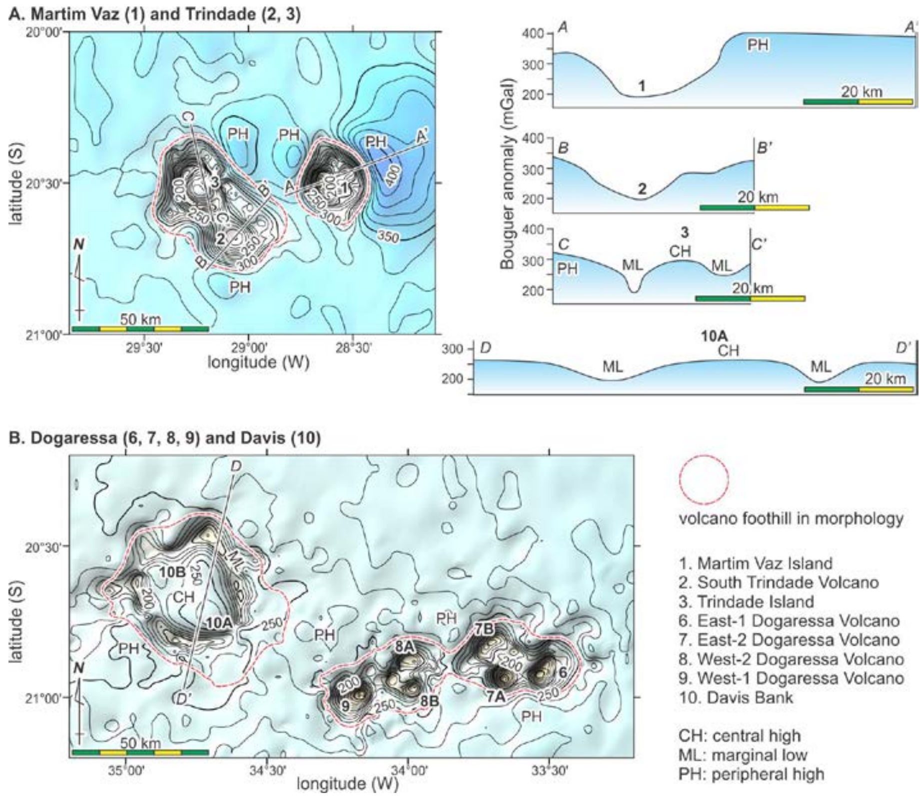

Figure 7.
Detailed Bouguer anomaly maps based on the TOPEX 14.1 for: A) Martim Vaz Island and Trindade Island; B) Dogaressa Bank and Davis Bank

The central Bouguer high is attributed to the high density zone along the central conduit. The most probable idea is multiple intrusions of radial dykes around the central conduit (Figure 8B, intrusions A). The total thickness of the intrusive bodies should be 5 km to 11 km. It is larger than the volcano height and the intrusive bodies must be present also in the upper crust (intrusions B). This model is similar to the idea of Ueda et al. (2008), which was based on the seismic cross-sections of seamounts of the western Pacific Ocean.

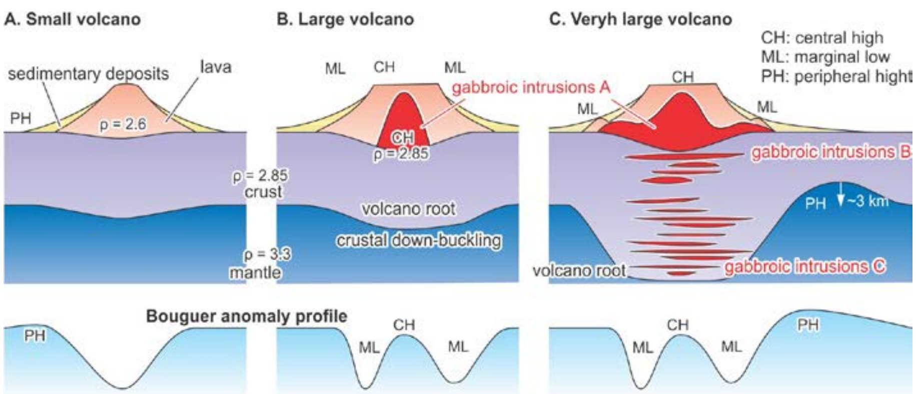

Figure 8.
Schematic illustrations for the proposed structure of the seamounts volcanic seamount: A) Small volcanoes with base diameter minor than 30 km; B) The volcanic edifices larger than 30 km in base diameter; C) Very large volcanic seamount. The real frequency of the intrusive bodies is much denser than the illustration.

The Figure 8 illustrates the model proposed by the authors. The small volcanoes without Bouguer central high are composed simply by lava flows and the seamount weight is sustained mainly by mechanical firmness of the basement (Figure 8A). The volcanoes

Martim Vaz (1), South Trindade (2), and West Columbia (5) represent this stage.

When the volcano grows-up, the magma ascension to the surface becomes difficult because of the elevated weight of the volcanic edifice. The magma intrudes along the central conduit in form of multiple radial dyke systems from the top to the base, constituting the central Bouguer high (Figure 8B). The seamount is still sustained mainly by the mechanical firmness of the basement. The crustal down-buckling increases and the peripheral high becomes notable. The Trindade (3) represents this stage. According to further growth, the central eruptions become less expressive and the intrusions become more intense. The intrusions occur also beneath the volcanic edifice, forming lateral cones. The heavy seamount is sustained mainly by isostatic equilibrium of large and deep volcano root. Davis Bank (10) and Vitória-Congress composite seamount (17, 18) represent this stage.

Kaneda et al. (2010) presented shipborne-based deep seismic cross-sections for the seamounts of Western Pacific Ocean. For the small seamounts, the crustal down-bucking is low, only of few kilometers. Almost all seamounts have cone-shaped high seismic velocity zone along the central conduit, which should correspond to the gabbroic radial dykes. The P-wave velocity beneath the seamount bodies is faster than that of the oceanic crust, either in the crust or below the Moho. The seamounts larger than 50 km in base diameter have large volcano root with relative depth of about 6 km in the mantle. The volcanic and subvolcanic structures of these seamounts agree well to the proposed gravimetric model of the volcanic seamounts of the Vitória-Trindade Chain.

Conclusion

The gravimetric analyses for the Vitória-Trindade Chain based on the satellite-derived data lead the authors to the following conclusion.

1. The magmatism and tectonism of the Vitória-Trindade Chain are strong at the western corner and become less intense to east. It is evidenced by size and frequency of the volcanoes, intensity of the regional Bouguer anomaly low, and height and width of the basement topographic uplift.
2. The small seamounts have Bouguer anomaly lower than the adjacent area, showing funnel-shaped depression. They are formed by central eruptions of lava flows and the weight is sustained mainly by mechanical firmness of the basement.
3. The volcanoes larger than 30 km in diameter show ring-like Bouguer structure composed of central high and marginal low. The central high is attributed to repeated intrusions of radial dykes around the central conduit. The seamounts are supported mainly by mechanical firmness and partially by isostatic compensation of crustal down-buckling.
4. Very large volcanoes have bull's eye-like low Bouguer depressions along the marginal low, which are attributed possibly to lateral cones buried by sedimentary deposits. The radial dykes intrude in the basal level of the volcanic edifice causing lateral eruptions. The crustal down-buckling and isostatic compensation are relevant.
5. On the foot of the volcanic edifices, there is the area with Bouguer anomaly 20 to 40 mGal higher than the adjacent abyssal plane, called peripheral high. It could be the rebound of the crustal down-buckling by seamount weight.

Acknowledgement

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