3D Density Structure of the Davis Bank along the Vitória-Trindade Chain, Southwestern Atlantic-Brazil

Onofre H. D. J. das Flores[1,3], Alanna C. Dutra[1], Eduardo R. V. Rocha-Júnior[1], Anderson C. dos Santos[2]
Vinicius A. R. Oliveira[1]
[1]Federal University of Bahia, Brazil
[2]Universidade do Estado do Rio de Janeiro, Brazil
[3]Lúrio University, Mozambique

Abstract

The Vitória-Trindade Chillies in southeastern Brazil, spanning between 17ºS and 20ºS in the Atlantic Ocean. This study unveils a new 3D density structure model for Davis Bank along the Vitória-Trindade Chain (VTC) in the South Atlantic. We use 3D gravity inversion to delineate the density distribution and unveil its internal architecture. Our results highlight a consistent high-density region in the central part of Davis Bank, suggesting a potential link to volcanic activity and indicating conduits for the ascent of magma from the mantle to the surface.

Introduction

The Vitória-Trindade Chain (VTC) in southeastern Brazil comprises various underwater structures that are important for understanding the Earth's dynamics and geological evolution of the area. Its origin is a subject of intense debate among researchers, with different theories proposed. Some posit that it stems from the separation of the South American and African tectonic plates (Richetti et al., 2018; Mohriak et al., 2022; Bonifacio et al., 2023), while others interpret it as a volcanic trail (O'Connor & Duncan, 1990; Pires et al., 2016). Recent studies suggest a connection to a compositional anomaly in the mantle, characterized by a mixture primarily sourced from depleted asthenospheric mantle represented by the DMM metasomatized by an Enriched Mantle I (EMI) component and potentially another HIMU-type constituent (e.g., Maia et al., 2022; Quaresma et al., 2023).

Although the Vitória Chain has been the subject of numerous geophysical studies (fe.g., Alves et al., 2006; Stanton et al., 2021; Szameitat et al., 2023), there is still no current literature model representing the 3D density structure for Davis Bank. Therefore, this study was carried out to fill this gap. We used 3D gravimetric inversion to estimate depth and volume and generate the density contrast model. The 3D gravimetric inversion approach provides a deeper understanding of the characteristics of this structure, enriching our understanding of its origin, evolution, and potential geodynamic implications.

Davis Bank, situated at an altitude of 4,000 m in the central region of the VTC, boasts a conical shape with a circular base, formed during the Miocene epoch (Quaresma et al., 2023; Rego et al., 2021). Comprising primarily of basanitic rocks alongside more evolved tephrites, these formations crystallized from fractionated liquids, exhibiting a range of compositions. Silica (SiO2) content spans 40.9 to 47.6 wt.%, while magnesium oxide (MgO) ranges from 3.6 to 9.6 wt.%. Noteworthy is their significant enrichment in light rare earth elements (LREE) and large-ion lithophile elements (LILE) (Maia et al., 2021; Quaresma et al., 2023). Characterized as fine-grained melanocratic vesicular basalts (Santos et al., 2003), the chronological age, determined through the $^{40}Ar/^{39}Ar$ dating method, is estimated at 21 million years (Quaresma et al., 2023; Rego et al., 2021)

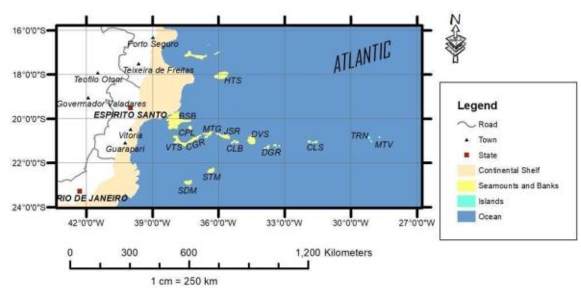

Figura 1- Location map of the Abrolhos Magmatic Province (AMP) and the Vitória-Trindade Chain (VTC). Some of the most significant seamounts are listed from west to east: Besnard Bank (BSB), Champlain Seamount (CPL), Vitoria Seamount (VTS), Congress Bank (CGR), Montague Seamount (MTG), Jaseur Seamount (JSR), Columbia Bank (CLB), Davis Bank (DVS), Dogaressa Bank (DGR); Columbia Seamount (CLS), Trindade Island (TRN), Martin Vaz Island (MTV), São Tomé Seamo Seamount (STM), Hotspur Seamount (HTS), and Admiral Saldanha Seamount (SDM).

Methodology

<u>Data description and processing</u>

We used gravity data, free-air, and Bouguer anomalies to develop this work. The Bouguer anomaly was calculated from the free-air anomaly acquired from satellites using global marine gravity databases with a resolution of 1 arc-minute (Sandwell et al., 2014). Residual-regional separation has been done to distinguish the gravitational sources observed in the total field into residual sources representing shallow features and regional sources reflecting deep structures. To achieve this, we applied the least squares polynomial fitting technique, and the result of the residual field obtained by this procedure is presented in Figure 2. In this figure, we observed a high gravimetric anomaly characterizing the volcanic buildings of VTC compared to their surroundings. Additionally, the AMP presents a high gravimetric signature that relates to the volcanic buildings of VTC, suggesting a geological connection between them.

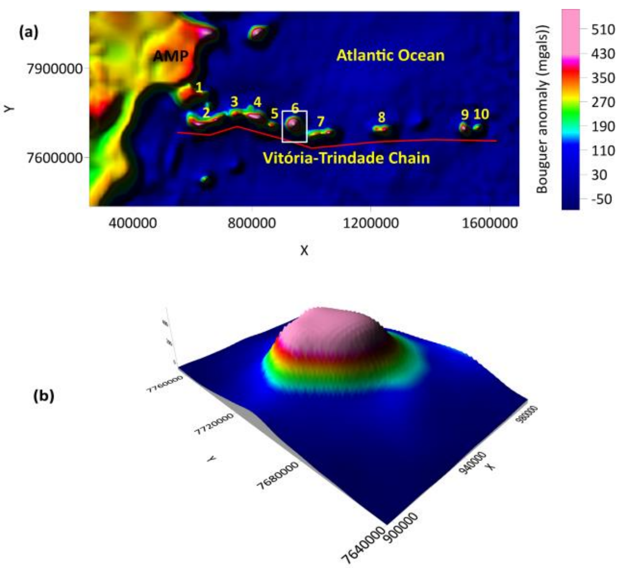

Figure 2 - (a) Map of residual gravity Bouguer anomaly. (b) Davis Bank residual Bouguer anomaly extracted from the blank rectangle shown on the map (a). The red line and the numbers highlighted in yellow represent the VTC and its main volcanic edifices. Abrolhos Magmatic Province (AMP), Besnard Bank (1), Vitória Seamount (2), Montague Seamount (3), Jaseur Seamount (4), Columbia Bank (5), Davis Bank (6), Dogaressa Bank (7); Columbia Seamount (8), Trindade Island (9), Martin-Vaz Island (10).

In addition to gravimetric data, we have also used topography/bathymetry data. The data was also obtained from a global database, namely the ETOPO database (Amante & Eakins, 2009), with a resolution of 1 minute (Figure 3). This figure shows that the MPA is characterized by high topography, reaching around 100m. On the other hand, it can be seen that the volcanic buildings are also characterized by a high topographic/bathymetric signature, identical to that observed in the MPA. The Atlantic Ocean is characterized by a negative bathymetry that varies between -5,500 and 3,500 m.

Figure 3 - Maps of topography/bathymetry. The red line and the numbers highlighted in yellow represent the VTC and its main volcanic edifices. Abrolhos Magmatic Province (AMP), Besnard Bank (1), Vitória Seamount (2), Montague Seamount (3), Jaseur Seamount (4), Columbia Bank (5), Davis Bank (6), Dogaressa Bank (7); Columbia Seamount (8), Trindade Island (9), Martin-Vaz Island (10).

<u>Method</u>

The inversion was performed using the oasis montaj® software through the VOXI tool. This tool allows for geophysical inversions to be executed in the cloud using a Cartesian cell cutting (CCC) approach and an iterative weighting inversion algorithm. This algorithm was first proposed by Lawson (1961) and refined by Ingram et al. (2003), and by Ellis and Macleod (2013). The inversion iterations are repeated until the difference between the average gravity of the inverted density model and the expected model is minimized to an acceptable level.

During the inversion, we incorporated density constraints from previous geological studies of volcanic rocks into the VTC, making our solutions more realistic. Positive density values were set at 0 at the bottom and 3.3 g/cm³ at the top, thus avoiding negative results.

Results

To analyze the geometric configuration, depth, and volume of the Davis Bank and generate its density contrast model, we performed a 3D gravimetric inversion. Initially, the inversion was carried out unconstrained in the Oasis Montaj software, using a cell resolution of X=35, Y=45, and initial Z=10. This process required 13 complete iterations and took 6 minutes and 59 seconds. The parameters related to the inversion mesh are shown in table 1. The results, shown in Figure 4, indicate that the DVS region contains rocks with density contrasts ranging from -0.845 to 5.6835 g/cm³.

The model reveals three distinct rock structures surrounding the DVS. Two structures exhibit negative contrasts, highlighted in blue in the representation. At the same time, one shows a positive contrast (Figure 4). Regarding morphology, the Davis Bank lacks a defined geometric shape but displays peaks with conical features and trunks at its top. Conversely, the surrounding rock structures exhibit well-defined conical shapes (Figure 4). Despite the depth observed in the bathymetry data, the inversion results suggest that the estimated depth of the DVS is approximately 14 km. However, this model did not allow for estimating the DVS's volume, as it was impossible to separate it from its surrounding structures.

Table 1- Parameters related to the inverse modeling mesh of Davis Bank. All parameters are in the international system.

	dx	dy	dz
Cell sizes	2500	2500	1250
Dimension	35	45	10
Min	902161.8	7650626.2	-14271.9
Max	987113.9	7760056.1	-17.8

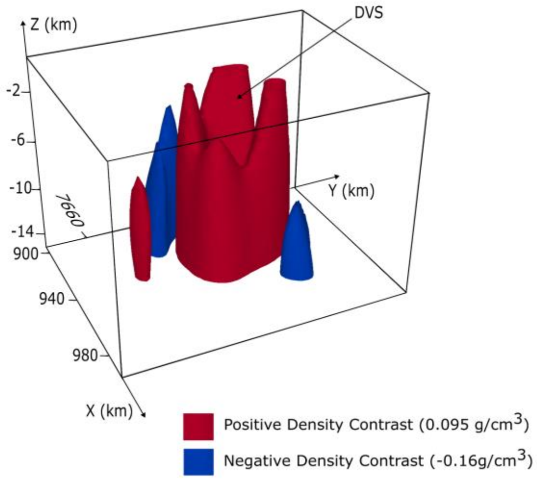

Figure 4 - The Density Contrast Model in g/cm³ obtained from the unconstrained inversion for the Davis Bank.

After finishing the unconstrained inversion, we proceeded with the constrained inversion, incorporating the limitations specified in the methodology. This inversion was completed after 12 iterations, taking 11 minutes and 37 seconds with the imposition of these constraints. The results are depicted in Figure 5.

In contrast to the observations from the unconstrained inversion, the results indicate that the DVS has a distinct morphology resembling a volcanic edifice, exhibiting variations in density contrast across its geological structure. These results suggest that the DVS assumes the geometric shape of a truncated cone with a larger and smaller base (Figure 5). This nearly conical form implies a geomorphological evolution associated with successive eruptive episodes in the VTC over time. Furthermore, our analysis unveils a density distribution wherein the central region displays elevated values, reaching 2.1146 g/cm³. Concurrently, the peripheral areas showcase diverse densities, with the lowest registering around 0 g/cm³. The heightened density observed in the central zone could be linked to basaltic magma chamber/magma flows, contrasting with the surrounding sediments and reflecting the internal dynamics of volcanism in the VTC locale.

On the other hand, the diminished density noted in the shallower regions of the model corroborates sedimentary interpretations. The denser regions originate from deeper sources (Figure 5). These findings align with those obtained in the unconstrained inversion, where the estimated depth of the DVS was 14 km. Additionally, the total volume estimated for the DVS amounted to 6078 km³.

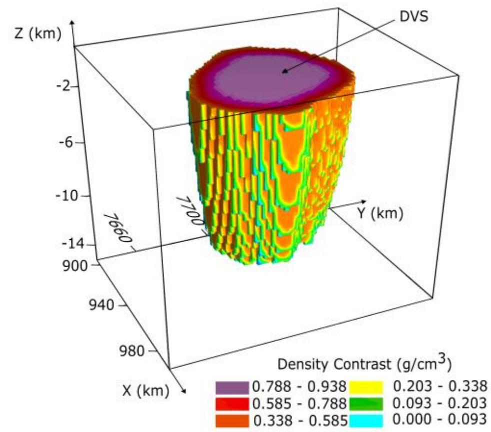

Figure 5 - Density contrast model derived from the inversion with positivity restriction on the density of the Davis Bank.

Discussion and Conclusion

This study investigated the delineation of structures within the Vitória-Trindade Chain, primarily focusing on Davis Bank. Gravimetric and bathymetric data were analyzed using geophysical inversion techniques. The results highlight distinct geological attributes, with central elevations in the density-contrast models exhibiting higher contrasts. These high-density contrasts are typically interpreted as materials from the Earth's mantle. These materials may ascend towards the surface through fracturing or migration along grain boundaries, eventually emerging at the surface. During this process, cooling may occur, resulting in solidification. Previous studies suggest that the formation of the Vitória-Trindade Chain was due to volcanism and structural control of the Vitória-Trindade fracture zone, facilitating magma percolation and the formation of various stationary points (Alves et al., 2006; Dos Santos et al., 2022).

Furthermore, studies by Marques et al. (1999), Siebel et al. (2000), and Quaresma et al. (2023) indicate that the magmatic rocks found in the Vitória-Trindade Chain exhibit geochemical signatures characteristic of oceanic island basalts. These rocks are derived from magmas originating from a source similar to the asthenosphere (DMM), which was metasomatized by recycled components (represented by EMI). This explains the high density observed in the central part of the model.

Regarding depth, a study by Rego et al. (2021) using geothermobarometry suggests that the magma chamber of Davis Bank is located at a depth of 12-30 km. These results are consistent with those calculated by our inversion, as we estimate a 14 km depth extending to the mantle. The estimated volume for Davis Bank is ca. 6,078 km³. The main results are:

- The model showed high density contrast in the central part, which is correlated with a conduit for magma ascent from the mantle to the surface.
- The estimated depth and volume for Davis Bank are 14 km and 6,078 km³, respectively.

Acknowledgements

We would like to express our gratitude to the Center for Research in Geophysics and Geology, Institute of Geosciences, as well as to the Laboratory of Applied Nuclear Physics and the Institute of Physics at the Federal University of Bahia, for generously providing access to computers and physical space for this research.

References

Alves, E.C., Maia, M., Sichel, S.E., Campos, C.M.P., 2006. Zona de Fratura de Vitória-Trindade no Atlântico Sudeste e suas implicações tectônicas. Rev. Bras. Geofís. 24,117–127.

Amante, C., Eakins, B.W., 2009. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24. National Geophysical Data Center, NOAA.

Bonifacio, J. F., Ganade, C. E., dos Santos, A. C., & da Trindade, R. I. F. (2023). Review and critical assessment on plate reconstruction models for the South Atlantic. Earth-Science Reviews, 238, 104333.

Ellis, R., MacLeod, I., 2013. Constrained voxel inversion using the Cartesian Cut Cell method. Proceedings of the 23rd International Geophysical Conference and Exhibition, Melbourne, Victoria, Australia, pp. 1–4.

Ingram, D., Causon, D., Mingham, C., 2003. Developments in Cartesian cut cell methods. Math. Comput. Simul. 61, 561–572.

Lawson, C.L., 1961. Ph.D dissertation. Univ. Calif.

Maia, T. M., dos Santos, A. C., Valente, S. C., Rocha-Júnior, E. R. V., de Barros, G. P. W., Heilbron, M., Arena, M., 2022. Abrolhos magmatic province petrogenesis and its link with the Vitória-Trindade Chain, southeast Brazilian margin, South Atlantic ocean. Journal of South American Earth Sciences, 120, 104075,

Marques, L.S., Ulbrich, M.N.C., Ruberti, E., Tassinari, C.G., 1999. Petrology, geochemistry and Sr-Nd isotopes of the trindade and Martin Vaz volcanic rocks
(southern Atlantic Ocean). J. Volcanol. Geoth. Res. 93, 191–216.

Motoki, A., Motoki, K. F., & de Melo, D. P., 2012. Caracterização da morfologia submarina da Cadeia Vitória-Trindade e áreas adjacentes, ES, com base na batimetria predita do TOPO versão 14.1. Revista Brasileira de Geomorfologia, 13(2).

Mohriak, W.U., de Almeida, J.C.H., Gordon, A.C., 2022. South Atlantic ocean: postbreakup configuration and Cenozoic magmatism. In: Meso-Cenozoic Brazilian Offshore Magmatism. Academic Press, pp. 1–45.

O'Connor JM & Duncan RA. 1990. Evolution of the Walvis Ridge – Rio Grande rise hot spot system: Implication for African and South American plate motions over plumes. J. Geophys. Res., 95: 17475–17502.

Pires, G.L.C., Bongiolo, E.M., 2016. The nephelinitic–phonolitic volcanism of the Trindade Island (South Atlantic Ocean): review of the stratigraphy, and inferences on the volcanic styles and sources of nephelinites. J. S. Am. Earth Sci. 72, 49–62.

Quaresma, G. D. O. A., dos Santos, A. C., Rocha-Júnior, E. R. V., Bonifácio, J., Rego, C. A. Q., Mata, J., ... & Geraldes, M. C., 2023. Isotopic constraints on Davis bank, Vitória-Trindade Ridge: A Revised Petrogenetic Model. Journal of South American Earth Sciences, 122,

Rego, C. A. Q., Quaresma, G. D. O. A., dos Santos, A. C., Mohriak, W. U., de Jesus, J. V. M., de Oliveira Rodrigues, S. W., 2021. Davis Bank geodynamic context, South Atlantic Ocean: Insights into the Vitória-Trindade Ridge evolution. Journal of South American Earth Sciences, 112, 103620.

Sandwell, D. T., Müller, R. D., Smith, W. H. F., Garcia, E. and Francis, R., 2014. New global marine gravity models from Cryo-Sat-2 and jason-1 reveal buried tectonic structures. Science, Vol. 346, 6205, pp. 65-67.

Siebel, W., Becchio, R., Volker, F., Hansen, M.A.F., Viramonte, J., Trumbull, R.B.,
Haase, G., Zimmer, M., 2000. Trindade and Martin Vaz islands, South Atlantic:
isotopic (Sr, Nd, Pb) and trace element constraints on plume related magmatism.
J. S. Am. Earth Sci. 13, 79–103.

Stanton, N., Gordon, A., Cardozo, C., Kusznir, N., 2021. Morphostructure, emplacement and duration of the Abrolhos Magmatic Province: a geophysical analysis of the largest post-breakup magmatism of the South-Eastern Brazilian margin. Mar. Petrol. Geol. 133, 105230.

Szameitat, L. S. A., Heilbron, M., De Aragão, M. A. N. F., Manatschal, G., Ferreira, F. J. F., dos Santos, A. C., & Mohriak, W. U. (2023). Geophysical evidence for lithospheric scale asymmetry and inherited mantle in the SE Brazilian-Angola and Newfoundland-Iberia rifted margins. Journal of South American Earth Sciences, 123, 104214.