Multi-geophysical investigation of the western portion of the Rio Grande Rise: 2D modeling of the basement relief using gravity data

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Abstract

The most extensive positive feature of the Brazilian seafloor, the Rio Grande Rise, separates the Brazilian and Argentine oceanic basins to the north and south, respectively. It also marks the eastern outer limit of the Brazilian Continental Shelf. The western, eastern, and central portions represent distinct geological histories influenced by intricate tectonic processes. However, due to limited research in the region, the exact origin of their basement remains inconclusive. The complex nature of the Rio Grande Rise has provided valuable scientific insights, particularly through regional and local gravity, enabling a comprehensive understanding of the subsurface at values scales. The scientific contribution of this study presents two 2D gravimetric models for the basement of the western portion of the Rio Grande Rise. Interpretations of seismic lines were used to constrain the proposed models, and a regional analysis using the global gravity model EIGEN 6C4 was also considered. The proposed density model of the western sector, resulting from this research, presents an unconventional configuration of the Moho interface, suggesting transitional characteristics between continental and oceanic crust. The modeled basement that best fits the gravity anomaly of the region is basically composed by basalts with some heterogeneities, which may exhibit some exaggeration but indicate behavior analogous to a shallower Moho in the Rio Grande Fault Zone, mantle activities beneath the Western Rio Grande Rise, and thinning of the basement associated with the Vema Channel, suggesting a former region of oceanic spreading, as indicated by some authors.

Introduction

The Rio Grande Rise presents itself as a collection of the largest physiographic features in the South Atlantic, extending over 700,000 km², and it regional context is responsible for delimiting the economically relevant oceanic region of Brazil. The Rio Grande Rise is divided into three areas with distinct morphologies and geological origins, as shown in Figure 1: the Western Rio Grande Rise, restricted to two structural highs of 500 km² that rise 1 km above the seafloor, the Eastern Rio Grande Rise, closer to the Mid-Atlantic Ridge by about 1000 km and connected by the Vema Channel, and the Central Rio Grande Rise, with an elliptical shape and a higher elevation towards the center, reaching approximately 4.4 km, located between the eastern and western regions of the Rio Grande Rise (PRAXEDES, 2020).

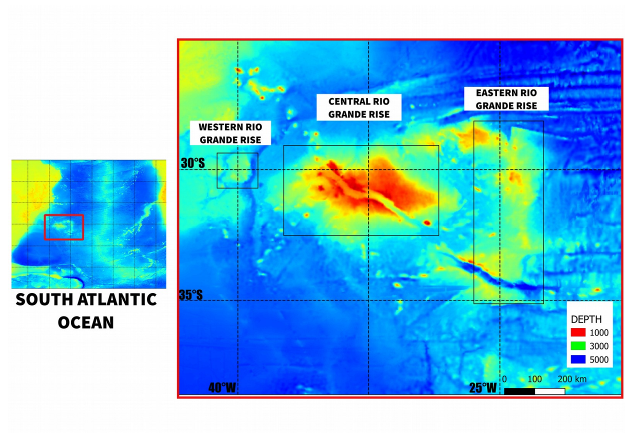

Figure 1 – Bathymetry of the Rio Grande Rise in the regional context of the South Atlantic.

The limited research conducted in the region has contributed to the existence of different theories regarding the origins of the Rio Grande Rise. Mohriak et al. (2010) proposed alternative interpretations for the geological basement of the Central Rio Grande Rise. These interprations include the possibility of a large igneous body resulting from hotspots, which are thermal anomalies in the mantle, or the presence of an isolated and residual continental crust left behind during the separation of the South American and African lithospheric plates.

Futhermore, Gamboa and Rabinowitz (1984) sugested that the Eastern Rio Grande Rise exhibits a distinctit dynamic due to its elongated shape in the north-south direction and its proximity to the Mid-Atlantic Ridge. This proximity has led to the theory that this particular body could be an aborted spreading center. This theory is suported by its similar position relative to another submerged geological feature known as the Walvis Ridge, which is located in the region opposite to the Mid-Atlantic spreading center. Praxedes and Castro (2020) inferred, through the correlation of seismic-stratigraphic sequences, that the Western Rio Grande Rise underwent the same tectonic-sedimentary forces acting on the central sector, which are responsible for its current configuration.

In light of the challenges mentioned thus far, it is proposed a more detailed investigation into the basement of the western portion of the Rio Grande Rise. For this purpose, gravity and seismic data provided by the Continental Shelf Survey Project, *Levantamento da Plataforma Continental (LEPLAC),* in Portuguese, were utilized to model the region's basement in order to estimate a density distribution that fits the Bouguer anomaly data in the area related to the Western Rio Grande Rise. By doing so, the aim is to contribute to the interpretation of the Rio Grande Rise in general from a geophysical standpoint.

Method

Initially, the region of the Rio Grande Rise was analyzed from a regional gravity perspective using the global gravity model. Then, the gravity response of the Western Rio Grande Rise was discussed based on marine gravimetry. Finally, the dimensions and densities of the basement of the Western Rio Grande Rise were inferred through 2D direct gravity modeling, using a seismic survey 500-0042 as a boundary and densities based in the literature as shown in Figure 2.

The analysis conducted in this research consisted of two datasets: the first group refers to regional gravity anomalies, and the second group consists of marine geophysical surveys of seismic and gravity origin.

DATASET	SOURCE	APLICATION
Bouguer anomaly	ICGEM	regional mass distribution
Free air anomaly		regional bathymetry,
Seismic 2D	LEPLAC	seafloor and basement depth,
Bouguer anomaly		parameter for 2D model adjustment
Free air anomaly		analysis of submarine relief behavior

Table 1 – Dataset used in the research and their objectives.

The regional gravity data are associated with the simple Bouguer anomaly and Free-Air anomaly functionals, calculated by the EIGEN-6C4 model, available at the International Centre for Global Earth Models with a resolution of 0.1°, within the boundaries between latitudes 26°S and 37°S and longitudes 46°W and 26.5°W. The marine survey data consist of the 500-0042 multichannel 2D seismic reflection line with a linear resolution of 50 meters, starting from the Brazilian continental margin and covering the Western Rio Grande Rise and the Vema Channel. The seismic line has been stacked and migrated in time, and two interpreted horizons in depth are provided, representing the seafloor and the basement top. Additionally, the gravity data reduced to Free-Air and Bouguer anomalies accompany the seismic survey, as indicated in Table 1.

Step 1

Database preparation: analysis of gravity anomalies obtained from ICGEM to characterize the mass distribution of the sectors of the Rio Grande Rise. The reflection seismic survey 500-0042, which was already interpreted by Praxedes and Castro (2020), and the associated marine gravimetry were selected.

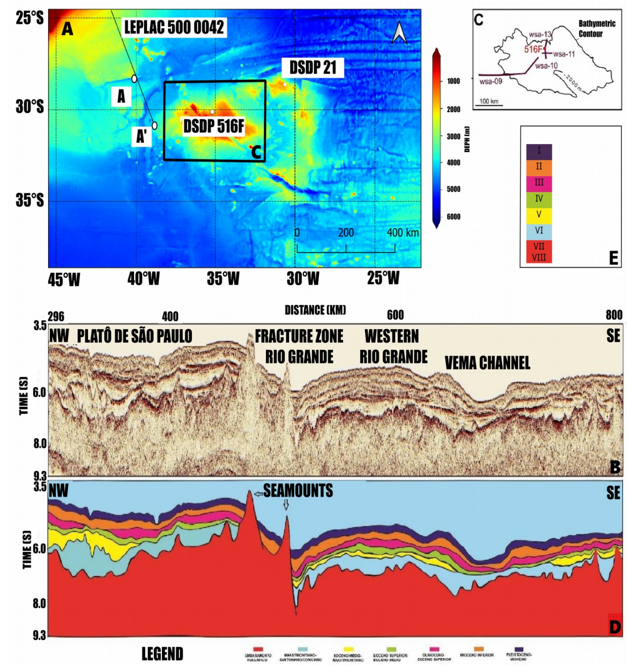

Figure 2 – Representation of the dataset applied in the methodology. In (A), the survey of the Brazilian Continental Shelf Survey Program with seismic and gravimetric data. In (B), the Leplac survey processed by Praxedes and Castro (2020). The result in (D) shows the correction of sedimentary layers from DSDP wells 516F and 21, shown in (E) along with the wsa seismic surveys (C).

Step 2

Seismic reflectors were converted into depth measurements, and both the interpreted seafloor and basement were analyzed together. This analysis facilitated the determination of the depths of the sedimentary package and the basement. These information were used as input to gravity modeling.

Step 3

In order to obtain a crustal model that explains both the geophysical data and geological information, a 2D gravity modeling was performed. The seismic line 500-0042 shown in Figure 2A was used, along with density values of the sedimentary cover sampled from borehole 516F of the Deep Sea Drilling Project and interpreted by Praxedes and Castro (2020). It should be noted that the densities of each polygonal section are known and constant. The densities of the crust and upper mantle were initially established according to Blake et al. (2008) as 2.9 g/cm³ and 3.4 g/cm³, respectively. In order to minimize errors in the modeling, modifications were made to the densities and internal geometries of the basement during this stage.

Step 4

Qualitative assessment was conducted to determine the acceptable root mean square (RMS) error. This assessment took into consideration variations in the geometry and density of the polygons forming the model, in order to achieve good misfit between the calculated gravity curves with the observed data.

At this stage, the densities and depths of the seafloor, basement, and Moho were defined. Subsequently, the reliability of the final model was verified by comparing it with information provided in other bibliographic references as Jeck et al. (2020), Pushcharovsky (2013) and Anderson (2006). This correlation process ensured the accuracy and consistency of the model.

Results

This chapter focuses on the presentation and discussion of the observed results obtained through qualitative analysis of global gravity model of the three sectors of Rio Grande Rise. Additionally, the marine gravity profile conducted over the western sector of the Rio Grande Rise is discussed, along with the development of a 2D density model to infer the mass distribution of the basement.

ICGEM Free-Air Anomaly

Figure 3 represents the response of the ICGEM model to the Free-Air gravity anomalies of the western, central, and eastern regions of the Rio Grande Rise. The relationship between topography and Free-Air anomaly allows for the differentiation of the major physiographic elements associated with the sectors of the Rio Grande Rise. These elements include the northern region of the Eastern Rio Grande Rise, the central region of the Central Rio Grande Rise, and two distinct bodies within the Western Rio Grande Rise.

Notably, significant structures like the Cruzeiro do Sul Rift, which is oriented in the NW-SE (proximal-distal) direction of the Central Rio Grande Rise, demonstrate a parallel association with the Free-Air anomaly. In this area, the Free-Air anomaly ranges from -50 to -100 mGal. Similarly, the Vema Channel exhibits a subtle negative contrast compared to its surrounding areas in terms of the Free-Air anomaly.

The prominent positive anomalies appear as embedded points over terrains with negative anomalies, such as the trail of points arranged in a SW-NE direction crossing the distal region of the Cruzeiro do Sul Rift. Similarly, another trail of positive anomaly points cuts through the central sector of the Rio Grande Rise, and another significant and isolated positive anomaly is located on the parallel of 32°S, between 34°W and 32°W, at the extremity of the Central Rio Grande Rise. A cluster of positive anomalies of 50 mGal is represented in an aggregation area in front of the Cruzeiro do Sul Rift. Finally, negative anomalies (-50 mGal) are observed around some of the positive topographic regions (50 mGal), such as the two parallel seamounts separating the northern and southern regions of the Western Rio Grande Rise.

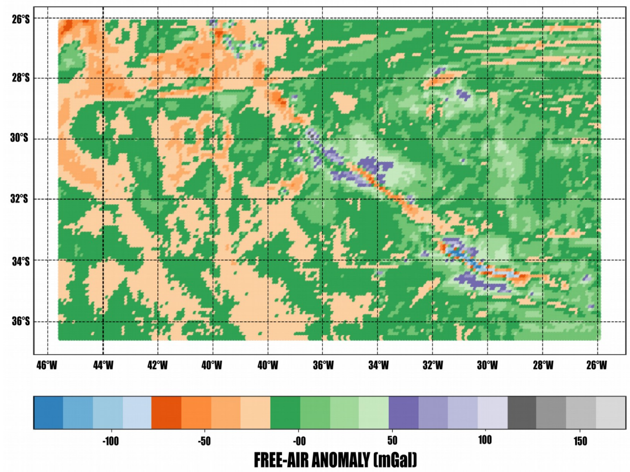

Figure 3 – Representation of the Free-Air anomaly of the Rio Grande Rise in relation to the ICGEM.

ICGEM Bouguer Anomaly

Figure 4 presents the Bouguer anomaly values from the ICGEM model for the portions that compose the Rio Grande Rise and its surroundings.

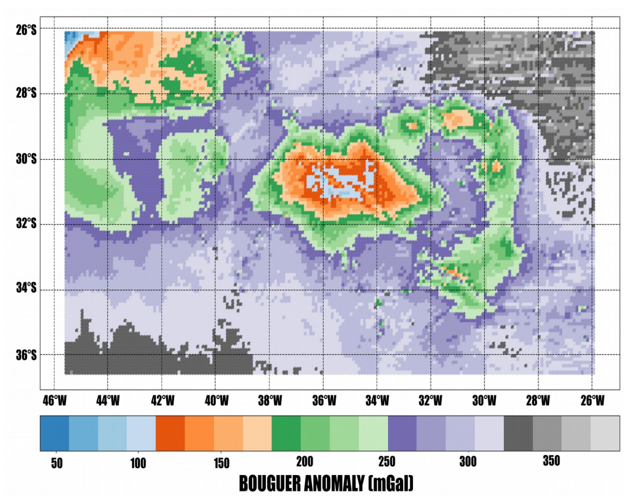

Figura 4 – Representação do funcional anomalia Bouguer do ICGEM.

In this figure, it can be observed that the amplitude of the anomalies varies between (50 and 350) mGal. Considering that the Bouguer anomaly represents all density contrasts, not only related to the mantle-crust interface but also the crust-sediment interface. However, the largest density variation present is associated with the mass differences between the mantle and crust.

The dataset presented in Figure 4 individualizes the three sectors of the Rio Grande Rise, ranging from (100 to 250) mGal, which cover the entire region and fit over terrains with values ranging from (260 to 300) mGal. The eastern sector is represented by a gravity of 200 mGal, with sections showing a significant decrease of 150 mGal. The Central Rio Grande Rise experiences a decrease in Bouguer gravity from the periphery to the center, with higher values ranging from (250 to 200) mGal, transitioning to (150 to 100) mGal, which are expected values for continental crust (JECK et al., 2020). The Western Rio Grande Rise exhibits a consistent gravitational behavior of 200 mGal throughout its contour. The Bouguer model overall displays the lowest gravity magnitudes in regions with higher structures, such as the central region of the Rio Grande Rise, highlighting the sets of seamounts from the Cruzeiro do Sul Rift in its proximal and distal parts, as well as the region cutting through the central sector in a NW-SE direction.

Marine Gravimetry

Figure 5 presents the gravity and depth information of the Rio Grande Fracture Zone to the western edge of the Central Rio Grande Rise. Regarding this figure, the Bouguer and Free-Air anomalies cover profile A-A' as they cross the Western Rio Grande Rise in a NW-SE direction, starting at the Rio Grande Fracture Zone, covering the Vema Channel, and ending in the peripheral region of the Central Rio Grande Rise, representing a distance of 300 km with a resolution of 50 meters.

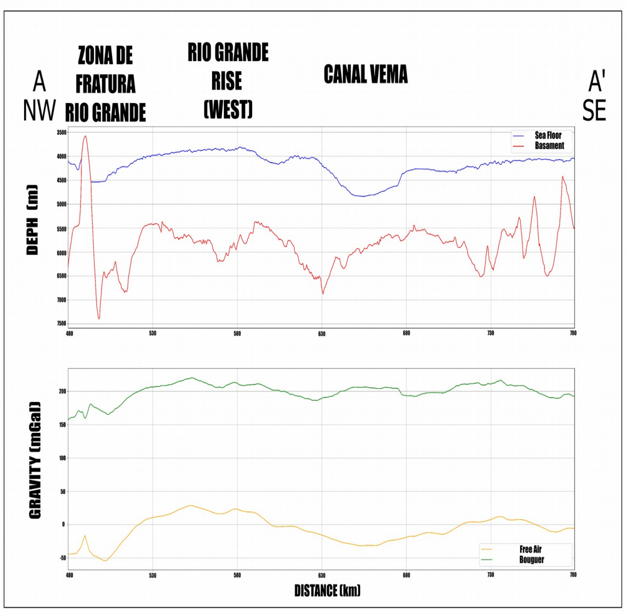

Figure 5 – Profile A-A' of the gravimetry of line 500-0042, including the seafloor and the top of the basement in depth.

The Free-Air values oscillate around 0 mGal within the range of -50 mGal and 50 mGal, as observed in Figure 3. The behavior of the Free-Air gravity generally shows a direct correspondence with depth.

2D Gravitational Model

The strategy adopted in this study was to infer two possible geological scenarios by observing the modeling that best corresponds to the observed data, that is, it presented the lowest RMS error possible considering the interventions implemented in the model.

Model 1

In general, the first scenario observed in Figure 6 had an RMS error of 16.707 and defines the depths of the mantle based on the modeling by Constantino et al. (2017). This model accommodates the crust in an approximately linear manner, with mantle intrusions reaching a maximum depth of 11.6 km with an estimated density of 3.39 g/cm³, and an average depth of 10 km.

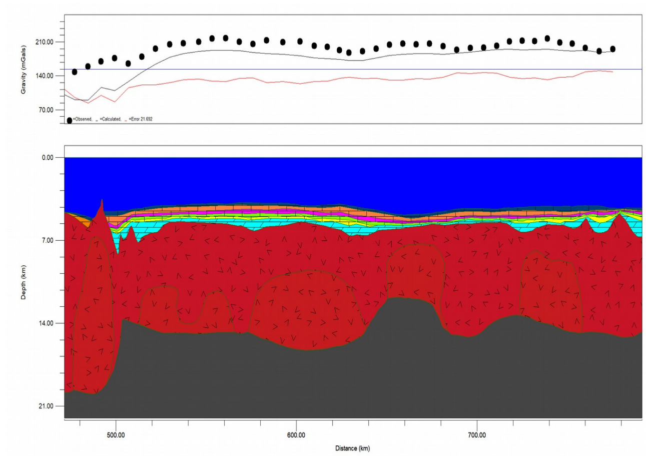

Figure 6 – Model 1 of the line 500-0042, which starts at the Rio Grande Fracture Zone and extends to the western edge of the Central Rio Grande Rise. The model represents, in profile, the sea in blue, the dimensions of the sedimentary package taken from the interpretation by Praxedes and Castro (2020), as well as the basement in red and the mantle in gray.

Model 2

According to Figure 7, the second calculated model yielded an RMS error of 6.057, achieved by introducing five heterogeneities in the basaltic basement, with these bodies being created to fit the model. However, it was not possible to identify these structures based on the reflectors present in the reference seismic line, which were also analyzed by Praxedes and Castro (2020) and represented in Figure 2D. At the northwest limit of the line, there is a gravity low of 150 mGal. This area of the profile exhibits a good fit for a heterogeneity with a density of 3.2 g/cm³ and a depth of 7 km.

The presence of a set of faults in this region could affect the measurements of the gravimeter sensitive to the surface, however, values around 150 mGal calculated by the ICGEM confirm this anomalous gravitational behavior. The Bouguer gravity over the Western Rio Grande Rise near the Fracture Zone reaches 214 mGal with a better fit for the heterogeneity of 3.1 g/cm³ and 11 km, as well as the neighboring anomaly of 207 mGal with a fitting body of 3.0 g/cm³ and 9.7 km depth. The two local gravity maxima identified would not be entirely justified by sedimentary coverage or basement uplift when comparing the two models.

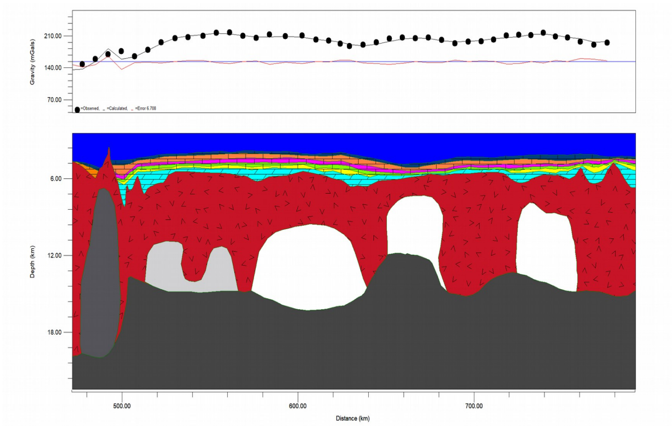

Figure 7 – 2D Model with the best fit. Heterogeneous bodies are present in the basement with densities distinct from the predominant density.

Over the Vema Channel and at the edge of the Central Rio Grande Rise, local gravity highs of (209 and 217) mGal occur, whose subsurface that best accommodates them presents bodies with 3.0 g/cm³ density and (7.3 and 7.9) km depth, respectively. The presence of these density anomalies in the crust could indicate the existence of mantle rocks at shallower depths or indicate that the crust-mantle interface is closer to the surface in a localized manner.

Final Interpreted Model

The final model of the Western Rio Grande Rise and its surroundings, with the density indications observed through bibliographic research and inferred from the Bouguer gravity fitting, is presented in Figure 8. It was possible to infer that the basement is of basaltic nature (ρ = 2.9 g/cm³) and undergoes thickening towards the continent, similar to what was found by Constantino et al. (2017). The Moho shows undulations in its geometry, partially justifying gravity anomalies located between the local bathymetric highs, which may indicate the presence of ancient cratonic or subduction zones, as discussed by Anderson (2006). The thinning of the crust towards the center of the image may correspond to, or even be conditioned by, the presence of the Vema Channel, as it is accompanied by an increase in lithospheric mantle thickness. The density anomalies identified in this section, although exaggerated due to possible lateral continuity, represent the sum of the response from bodies with varying shapes and depths, as reflected by the characteristics of the rocks composing them at the base of the heterogeneous crust, as observed in the depth indications in the basement represented in Figure 8.

This theory would apply best to the anomaly over the Fracture Zone as it presents an estimated density of 3.2 g/cm³. However, the anomalies also modeled under the West Rio Grande Rise, Vema Channel, and near the Central Rio Grande Rise indicate the presence of rocks that are typically denser than basalt.

The anomaly under the Vema Channel and Central Rio Grande Rise could indicate mantle activity during the spreading process of an ancient ocean, assuming the area is under a continental microplate, as suggested by Pushcharovsky (2013). Similarly, the anomalies under the West Rio Grande Rise may signal variations in the stretching of the basement, with the Moho closer to a continental mantle-crust interface rather than an oceanic mantle-crust interface, due to its proximity to the continental margin, as also indicated by the research of Jeck et al. (2020).

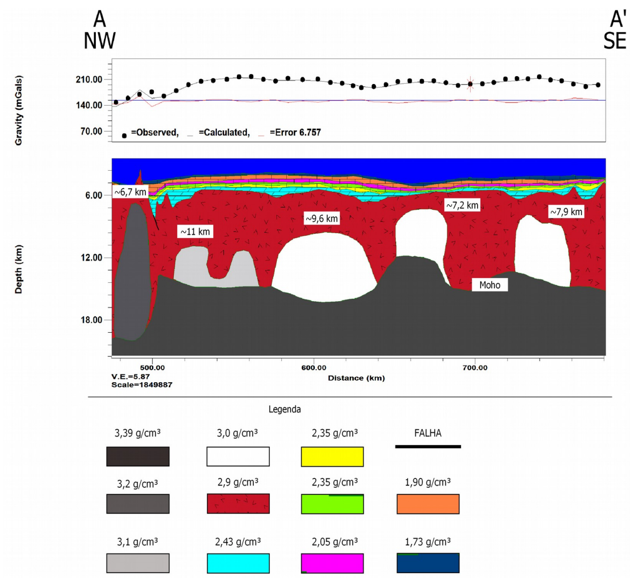

Figure 8 – Interpreted Model from Bouguer anomaly and seismic survey. Densities were identified based on what was observed in core samples with laterally correlated profiles.

Conclusions

The proposed methodology identifies the different geological structures of the Rio Grande Rise through the Bouguer anomaly from ICGEM. The central and eastern sectors exhibited behavior more similar to the continental shelf Bouguer anomaly. The more refined 2D gravimetric model incorporated five heterogeneities in the basement of the western sector. Finally, a visual inspection of the information represented in the profile (marine gravimetry) and map (regular grid of the model) indicated correspondence between the observed and calculated anomalies.

For the future, magnetic data will be also considered into a joint interpretation framework.

Acknowledgments

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