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DETECTION OF GROSS ERRORS IN THE GRAVIMETRIC DATABASE OF THE RIO GRANDE DO SUL STATE

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ABSTRACT. Since 1950, ground gravity data of the Rio Grande do Sul State (RS), Brazil, have been systematically collected by the Department of Geodesy of the Universidade Federal do Rio Grande do Sul (UFRGS) and other institutions in a total of 7.218 points. This paper proposes three methods for detection of gross errors in this database, based on: 1) the digital elevation model of Shuttle Radar Topography Mission (SRTM), 2) the Gravity Recovery and Climate Experiment (GRACE), and 3) the interpolated observations of ground gravity observations (Bouguer anomaly). The 1st method identified 217 points of altimetry, representing 3.00% of the database. The 2nd identified 645 points of gravity observations, representing 8.93% of the database. The 3rd method identified 60 points of land gravimetric observations, representing 0.83% of the database. The criterion to eliminate the observations was based on the recognition of coincident outliers in, at least, 2 methods. The matching points of coarse errors among altimetry, gravity and Bouguer anomaly were grouped in 177 points, representing 2.45% of the database. These points were considered gross errors and were erased from the database. After cleaning the database, we focused in the preliminary interpretation of the Bouguer anomaly map of the RS, recognizing a direct association of the main regional geologic units with four well-defined geophysical domains.

Keywords: gravity, Bouguer anomalies, outliers, SRTM, GRACE.

RESUMO. Desde 1950, dados gravimétricos terrestres do Estado do Rio Grande do Sul (RS) têm sido sistematicamente coletados pelo Departamento de Geodésia da Universidade Federal do Rio Grande do Sul (UFRGS) e outras instituições, perfazendo um total de 7.218 pontos. Este trabalho propõe três métodos para detecção de erros grosseiros neste banco de dados, com base em: 1) no modelo digital de elevação da *Shuttle Radar Topography Mission* (SRTM), 2) no *Gravity Recovery and Climate Experiment* (GRACE) e 3) nas observações interpoladas de dados de anomalias Bouguer terrestre. O primeiro método identificou 217 pontos de altimetria, representando 3,00% do banco de dados. O segundo método identificou 645 pontos de gravidade, o que representa 8,93% da base de dados. O terceiro método identificou 60 pontos de observações de gravidade terrestre, o que representa 0,83% da base de dados. O critério para a eliminação de observações foi baseado na identificação de *outliers* coincidentes em, pelo menos, dois métodos. Os pontos correspondentes de erros grosseiros entre a gravidade, altimetria e anomalia Bouguer foram agrupados em 177 pontos, o que representa 2,45% do banco de dados total. Estes pontos foram considerados erros grosseiros, sendo eliminados da base de dados. Posteriormente, foi realizada uma interpretação preliminar do mapa de anomalia Bouguer do RS, reconhecendo-se uma associação direta entre as principais unidades geológicas, reveladas por quatro domínios geofísicos distintos.

Palavras-chave: gravimetria, anomalia Bouguer, observações discrepantes, SRTM, GRACE.

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INTRODUCTION

During the last years there has been a great contribution to the Earth's gravity field measurements by the use of satellite observations (Kahn, 1983; Featherstone, 2001). Studies show the importance to use orbital data, mainly in regions with scarce conventional data and in areas where there are no land stations. The gravity surveys are based on measurements of the variations of the Earth's gravity field, which consist in the attraction produced over the existing bodies on its surface (Blakely, 1996). Subsurface geologic structures are investigated on these variations caused by differences of the density of rocks at different depths.

In geophysical exploration the propagation of errors of gravimetric data may generate incorrect interpretations for the characterization of prospective bodies and structures of interest (Sproule et al., 2006). Since the gravity is a measure of acceleration, its measurement should simply involve the determinations of distance and time. But, such apparently simple measurements are not easily executable with the precision and accuracy required for gravimetric surveys. The measurement of an absolute gravity value is difficult and requires complex equipment, besides a long observation period. Thus, the incorrect identification of a target may result in an unnecessary and expensive investment, especially in areas of difficult access. The errors in gravity measurements may be caused by: 1) reading error; 2) data transcription error; 3) incorrect gravity reference station; and 4) incorrect 3D observation gravity coordinates.

Various techniques can be used to detect these gross errors and the evaluation of the reliability of a database. In general the statistical technique of residual exploratory analysis is very sensible to the presence of extreme values. But, even after eliminating those points, the presence of a non-stationary behavior with drift of the geological variables does not satisfy the formal requirements of statistics to validate a model or database and infer results according to the law of probabilities. According to Landim (2003) residual values from these variables exhibit spatial autocorrelation, leaving as sole solution the empirical or related determination of the probabilities present in the observations. Thus, the Z statistics of the normal or Gaussian distribution is not appropriate to infer results of the nature of these variables when the purpose is to detect outliers.

Based on these aspects, three databases were integrated for the elimination of discrepant observations from the residual analysis of histograms. For this purpose they were used three methods for the detection of gross errors and integrated visual analysis. Using the corrected data a Bouguer anomaly map from the Rio Grande do Sul State (RS) was generated for subsequent geologic validation of the geophysical information.

LOCATION AND GEOLOGIC ASPECTS OF THE STUDY AREA

The study area is located in the SW portion of the Rio Grande do Sul State (RS), Brazil, between latitudes –34° and –27°S, and longitudes –58° and –49°W (Fig. 1). The Figure 2 represents a sketch of the Geologic Map of RS, with geomorphologic limits. Generally, in the north and northeast regions of the RS occur basic and acid volcanic flows from the Paraná Basin. In the northeast portion there are the highest elevations of this plateau, reaching altitudes of approximately 1,400 m. Their borders correspond to the called Serra Geral boundary the coastal plain of the RS.

In the western portion of the State basalt rocks are predominant, besides outcrops of intertrap sandstones where altitudes do not reach more than 250 m. In the center of the State occurs the coverage of sedimentary rocks of the Paraná Province, forming a corridor that cuts the whole east-west portion of the area through low altitude lands. In the center-south portion of the RS occurs the Sul-Rio-Grandense Shield. Those are Precambrian igneous rocks from the crystalline basement. This area is formed, partially, by sequences of sedimentary rocks (conglomerates, sandstones and siltstones) and by volcanic rocks (rhyolites, andesites and volcanic tuffs) (Chemale Jr., 2000). The altitude of these regions does not reach more than 600 m. The eastern portion is formed by Cenozoic sedimentary deposits corresponding to a strip of sand with 622 km, with high occurrence of lagoons and lakes.

CHARACTERISTICS OF THE DATABASES

Ground Databases

The gravimetric database of the RS State is compounded by a total of 7,218 points acquired since the end of the 1950 decade and was built using data from various institutions: Geodesy Department of the Universidade Federal do Rio Grande do Sul (UFRGS), Instituto Brasileiro de Geografia e Estatística (IBGE), Observatório Nacional (ON) and Instituto de Astronomia e Geofísica from Universidade de São Paulo (IAG/USP), under others. The gravimetry variables present an average spacing of 2.5 km and were acquired with different equipment, between them, SCINTREX CG3 (resolution of 0.005 mGal) and LaCoste & Romberg (resolution of 0.01 mGal). The altimetry was obtained from data extracted from topographic maps in different scales, barometric surveys, geometric leveling, between others, whose expected minimum and maximum errors are of 0.1 m to 10 m, respectively. The Figure 3 presents the

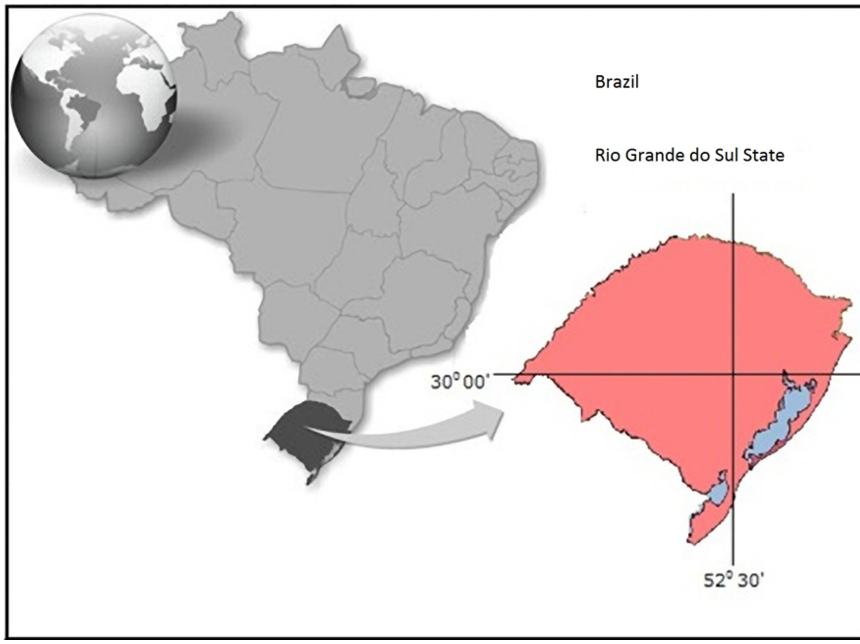

Figure 1 – Localization of the study site. Source: modified from <http://www.jama.com.br/localização.html>.

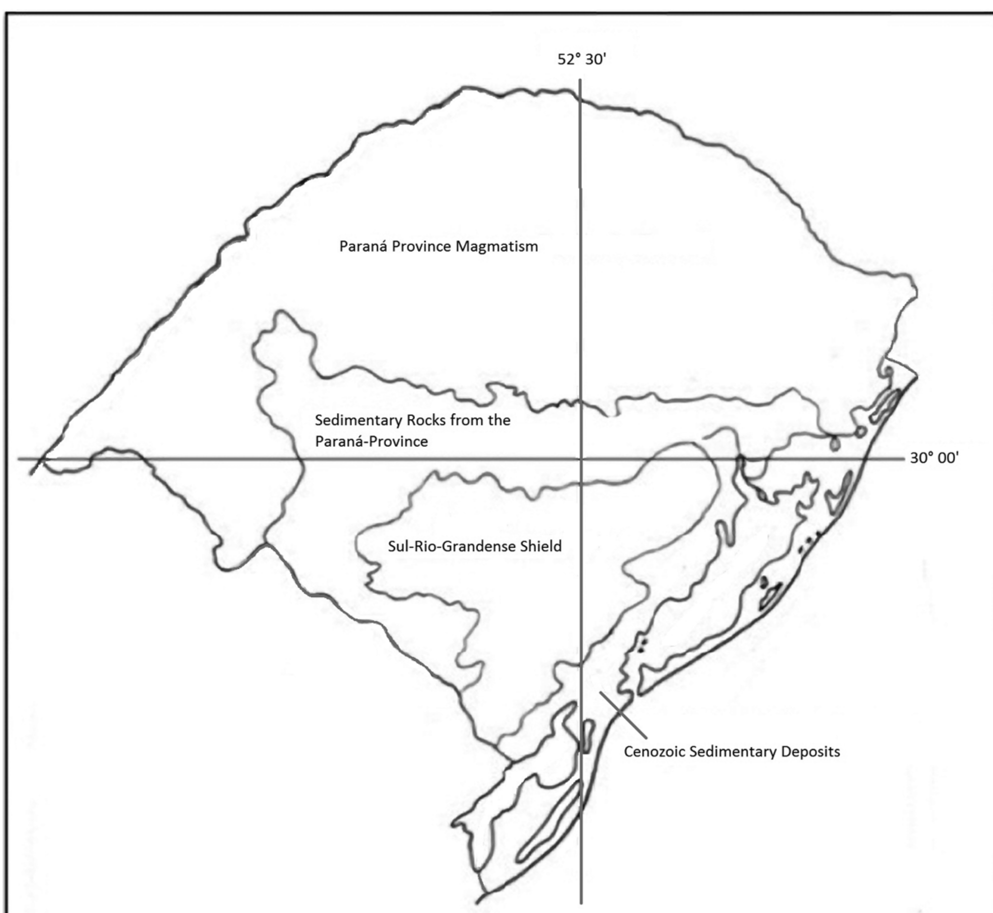

Figure 2 – RS simplified geological map. Source: modified from <http://www.museumin.ufrgs.br/MINNMineraisRS.htm>.

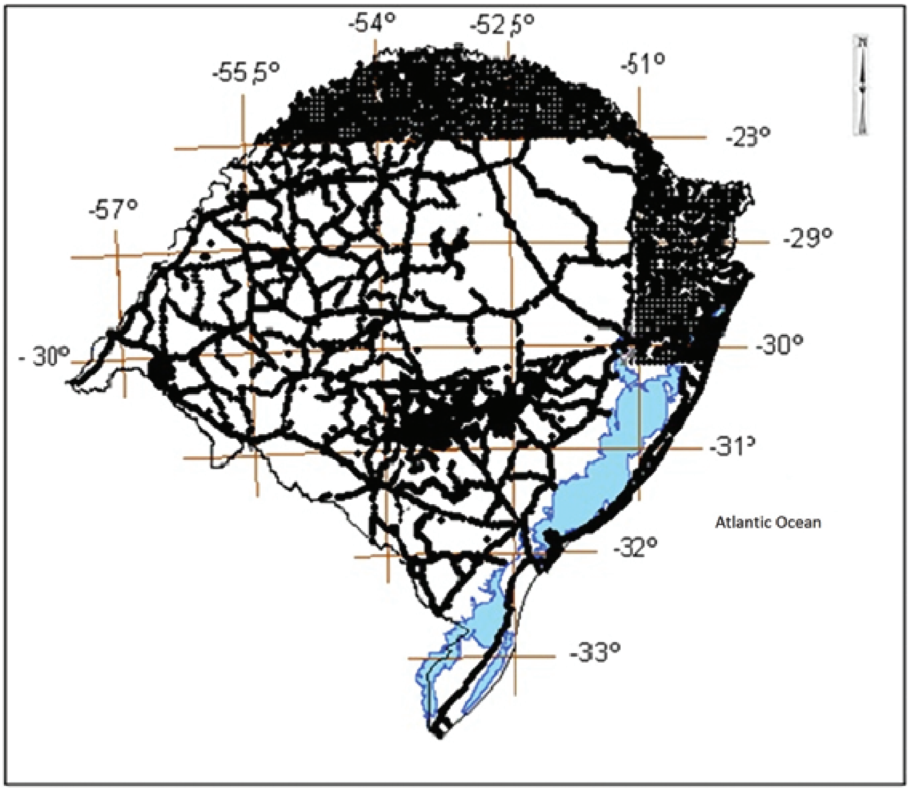

Figure 3 – Point distribution of the terrestrial gravimetric database from RS.

distribution of the original grid of readings, where Datum WGS1984 was the adopted geographic coordinate system.

Orbital and SRTM and grace databases

The Shuttle Radar Topography Mission (SRTM) database is part of a project between the National Imagery Mapping Agency (NIMA) and the National Aeronautics and Space Administration (NASA), whose purpose was to produce topographic digital data of 80% of the Earth's surface (area located between the latitudes 60°N and 56°S). The SRTM data generated elevation information every 1 second of arc (approximately 30 m) within geo-referenced grid in Latitude and Longitude. The images are available with 30 m resolution for the United States and of 90 m for Brazil and the other countries (NASA, 2008), with reference datum and ellipsoid related to the World Geodetic System 1984 (WGS84) (Hall et al., 2005). In accordance with the specifications of the SRTM mission, the digital elevation models were produced with a vertical precision of 16 m (NASA, 2008). The data from the Gravity Recovery and Climate Experiment mission (GRACE) are part of a project between NASA and the German Aerospatial Center (DLR), where two satellites launched in March 5, 2002 gathered data to determine the global gravity field at high resolution beyond temporal variations of the gravity measurements.

METHODS

As a general way the procedure for correction and interpretation of the variables of the database was held in 6 steps: 1) assembling the ground and orbital database and elimination of duplicate observations; 2) standardization of the variables and generation of the calculation of the theoretical gravity and the Bouguer anomaly; 3) calculation of the residuals with SRTM and GRACE data for each method; 4) integrated analysis of the databases; 5) generation of geo-referenced grids (xyz) for the processing and preparation of maps of the Bouguer anomaly and altimetry; and 6) interpretation of the geophysical response based on the geologic model established for the area.

Calculation of the Bouguer anomaly

According to Gemael (1999) the gravimetric anomaly is achieved through the equation $\Delta g = g_0 - \gamma$, where g_0 corresponds to the observed real gravity (ground observation), reduced to the geoid surface, and γ corresponds to the normal or theoretical gravity, obtained according to the latitude of the station over the spheroid surface. The value of the theoretical gravity was generated through the International Gravity Formula calculated over the reference ellipsoid of 1980 (Gemael, 1999):

$$\gamma_{80} = 978{,}0326776 * \big(1 + 0{,}005279041 * (\sin(\varphi))^2 + 0{,}000023272 * (\sin(\varphi))^4 + 0{,}000000126 * (\sin(\varphi))\big)^6$$

where φ is the latitude of the point in radians.

In this study, the Bouguer anomalies were calculated with the expression $\Delta g_b = g_o + 0{,}3086 * h - 0{,}1119 * h - \gamma$, where the second term corresponds to the Free-Air correction and the third term to the Bouguer correction, being "h" the altitude of the point, g_o and γ the values of observed real gravity and of the calculated theoretical gravity, respectively. The values were calculated for an average density of 2.67g/cm^3 (Gemael, 1999). The terrain correction was not considered, since its values are insignificant in the precision of the interpolation for this study.

Calculation of residuals

Three methods were used for the detection of gross errors of land gravimetric. The first method (M1) calculated the residuals between data from the digital elevation model from the interpolated SRTM and the altimetry observation data. The second method (M2) used interpolated data from the GRACE mission, comparing each gravity observation with the observations of the land gravity. The third method (M3) calculated the residuals from the crossed checking between the land gravity data of each observation of the calculated Bouguer anomaly and the interpolated Bouguer anomalies corresponding to the GRACE mission. The data interpolation for the three methods was made with the kriging method, with variogram adjusted for the spherical distribution model (Davis, 1973).

Statistical data treatment

The residuals calculated in M1, M2 and M3 were plotted in histograms. As previously mentioned the statistical treatment based on the standard for normal distribution of the gravimetric and altimetry residual observations is inadequate due to the high kurtosis of the data. Under these conditions a reasonable part of the altimetry data, for example, would be disposed due to the non-stochastic behavior of the local topography (Sproule et al., 2006).

Based on these aspects they were empirically defined the upper and lower thresholds which allowed the elimination of the discrepant points in each method (Table 1). The choice of thresholds was based in the elimination of points from the extremities of the distribution curve of the inflexion region demonstrated by the histogram for the 7,218 observations of raw data (Figs. 4, 5 and 6). The observations with suspected gross errors where cross checked between the three methods. The elimination of points occurred when occurred coincident identification in latitude and in longitude by at least two methods.

Table 1 – Decision thresholds for gross errors for the three methods used.

Residuals	Minimum (decision threshold)	Maximum (decision threshold)
M1	–90m	+90m
M2	–25mGal	+25mGal
M3	–12mGal	+12mGal

Integrated data treatment

Once eliminated the coincident points through latitude and longitude the Bouguer anomaly map and the altimetry map were generated, following the interpretation taking into consideration the geologic and geophysical information of the area.

RESULTS

The M1 method identified 217 residual points, corresponding to 3.00% of the total database. The M2 identified 645 points referring to 8.93% of the database; and M3 identified 60 points, representing 0.83% of the database. The Figures 4, 5 and 6 present the residual histograms resulting from the application of methods M1, M2 and M3, respectively. The cross checked residual statistics between the methods and percentages of excluded coincident observations were:

- M1 and M2: 2.0% (148 points)
- M2 and M3: 0.3% (23 points)
- M1 and M3: 0.1% (7 points)

Figure 7 shows the errors under the methods M1 and M2. The points between M1 and M2 were investigated and are related to altimetry errors, probably due to the lack of a leveling reference. The altitudes in this region are above 1,000 m consistent with the SRTM data.

Figure 8 presents the errors between methods M1M3 and M2M3. The points located in lower altitudes, identified by M2M3 in the region of the Sul-Rio-Grandense Shield and the north of the State, Paraná Province, are associated with gravity and anomaly errors. Such errors are expected due to the heterogeneity of the sources of the gravimetric databases from RS, as well as errors from M1M3.

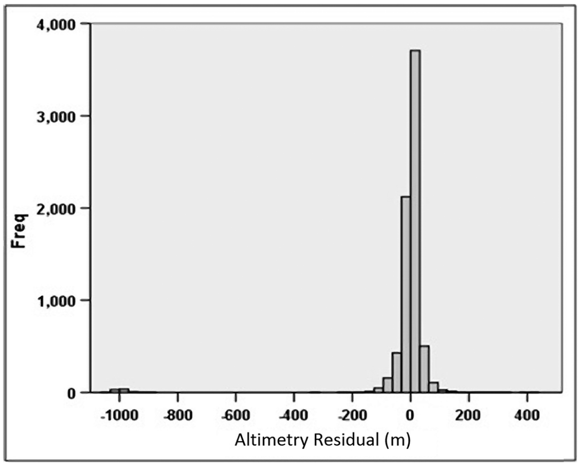

Figure 4 – Histogram of the differences between the elevation values of the 7.218 points and the respective SRTM points interpolated by the Krigagem method.

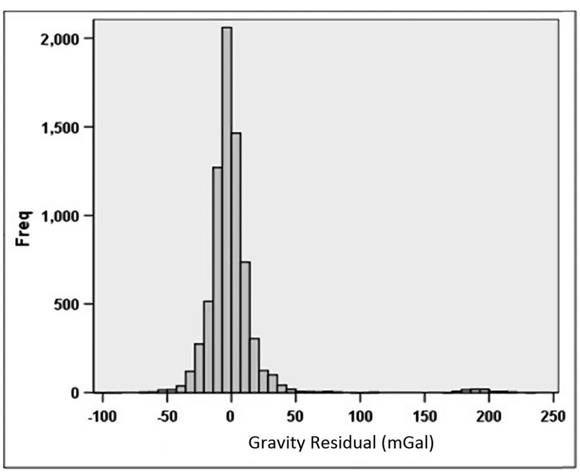

Figure 5 – Histogram of the differences between gravity values of the 7.218 points and the respective GRACE mission points interpolated by the Krigagem method.

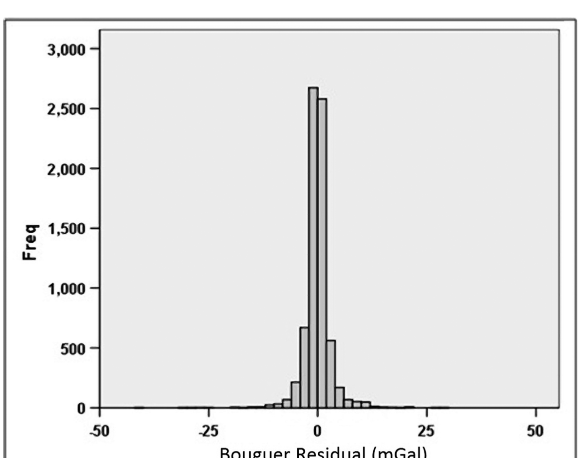

Figure 6 – Histogram of the differences between Bouguer anomaly values calculated from the 7.218 points and the respective Bouguer anomaly points interpolated by the Krigagem method.

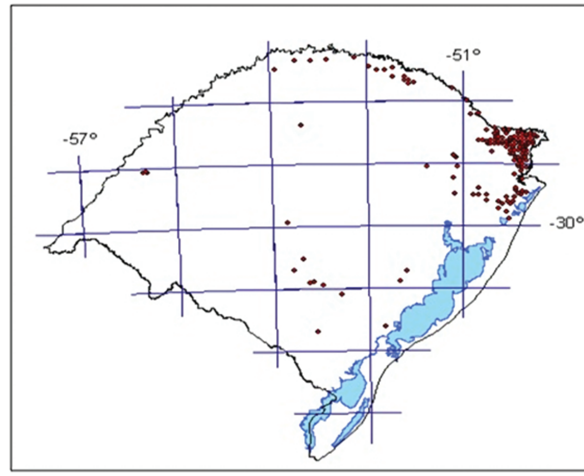

Figure 7 – Localization of the 148 points excluded by the residuals between altimetry and gravity (M1M2 methods).

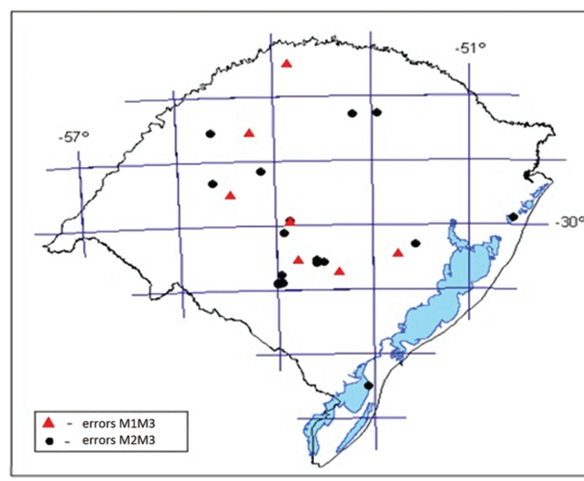

Figure 8 – Localization of the points excluded by M1M3 and M2M3.

The implicit subjectivity on the elimination of those points is recognized. Nevertheless, the high kurtosis of the data distribution does not allow the validation of a normal model for the procedure used for elimination of outliers. In the case of altimetry data (M1), the limit value of 90 m for the threshold elevation is much higher than the expected error of the accuracy of the digital elevation model of the SRTM was used (20 m) and of the land observations (0.1 m to 10 m).

In the same way, the 25 mGal threshold for the gravity (M2) is above the worst error which can be made in gravimetric observations (15 mGal to 20 mGal). Since the 12 mGal threshold for Bouguer anomaly data (M3) might have been a rigorous choice. However the low number of excluded points with method M3 makes the choice of this threshold less critical.

The sum of coincident points excluded by the methods M1, M2 and M3 totalized 178 points, considering that only one point

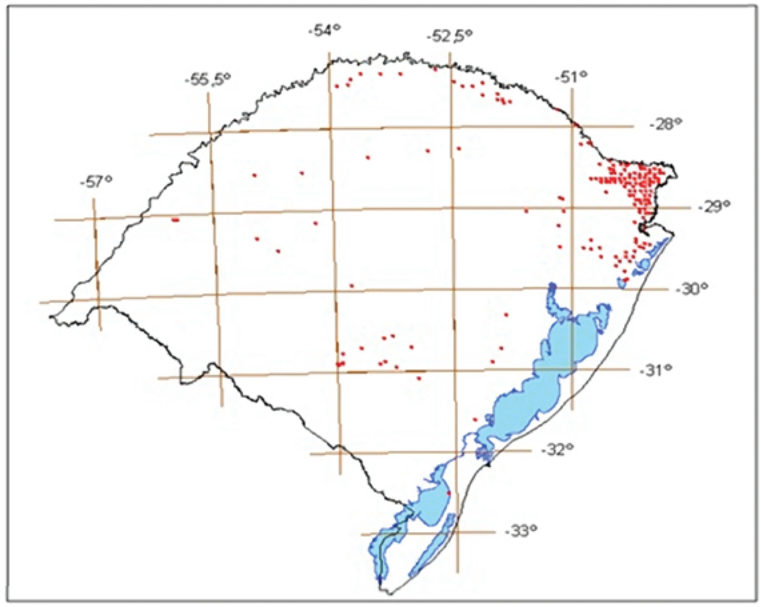

Figure 9 – Localization of the 177 coarse points deleted from the RS database, among/resulting from the three methods combined.

was common for the three methods. Thus, 176 points with discrepant values in altimetry, gravity and Bouguer anomaly were eliminated, representing 2.43% of the total database (Fig. 9).

Map of Bouguer anomaly and geophysical characterization

After the database cleaning the analysis of gravimetric response for the area, based on the existing geological information, started. Figure 10 presents the Bouguer anomaly map showing four well defined geophysical domains for the RS. In general, such domains present a strong correlation to the geology of the State, clearly separating the Sul-Rio-Grandense Shield from the volcanosedimentary units from the Paraná Province. Such domains were divided in D1, D2, D3 and D4.

Domain 1 – North-Northeast Portion

The Bouguer anomalies in D1 reach values between –90.3 mGal and –48 mGal. The altitudes are between 600 and 1,240 m approximately, with correlation inversely proportional to the values of the Bouguer anomaly. There is an exception for the NNE portion of this domain due to the presence of vesicular facies in the basalts that produces a reduction on the values of the Bouguer anomaly. This portion is in general associated to the basic magmatism of the Paraná Province producing values around –80 mGal and altitudes around 700 m. In the higher regions of this domain, above 900 m, occurs a significant variation of the Bouguer anomaly associated to the type of rock present in these places of higher altitudes.

Domain 2 – Center-Northwest Portion

Anomalies in D2 present values between –35 and –29 mGal and altitudes of no more than 500 m. Such domain is associated to the intermediate to acid flows of the Paraná Province with predominance of the last one. Comparing the geologic map (Fig. 2) to the Bouguer anomaly map (Fig. 10) it may be noticed a transitional limit in the southern portion of D2, showing a strong correlation with the presence of sedimentary rocks of the same province. The gravimetric relief is gentle corresponding to a topographic relief fairly homogeneous, represented by gentle hills (coxilhas), morphologically formatted by in basic volcanic rocks from the Serra Geral Formation and sedimentary rocks from the Paraná Province. The altitudes in this portion vary from 50 to 600 m approximately and this elevation decreases from the north to the center of the State. The most expressive anomalies of this domain are found near the lowest altitudes (central depression) no more than 400 m high.

The densities of the rocks existing in the highest region present variation averaging 2.09 to 3.17 g/cm^3, related to the basic volcanism of this domain. The densities of the rocks of the lowest region present a large average variation (1.92 to 2.70 g/cm^3)

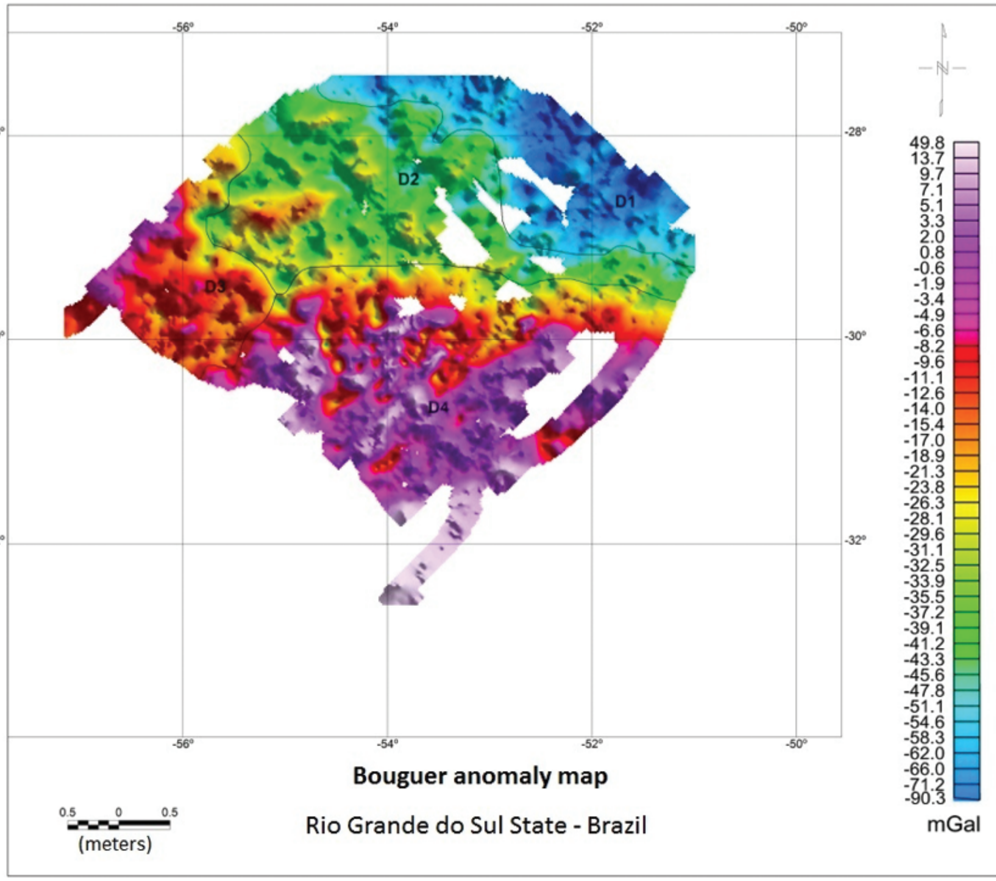

Figure 10 – Bouger anomaly map of RS showing gravimetric domains, characterized from the corrected database.

due to the occurrence of sedimentary rocks. This is related to the mineral composition and to the porosity and compaction degree as well.

Domain 3 – Extreme West Portion

The anomalies of D3 present value situated between –20 and 0.0 mGal with the highest values occurring in the western portion of the domain where the alluvial deposits occur and altitudes vary between 50 and 100 m. The anomalies' intensity decrease towards south of this domain where the altitudes reach up to 300 m in the transitional strip associated to the limit with the sedimentary rocks present in D4 domain. The Extreme West of the RS State is formed by flows with intermediate to acid composition ranging between andesites and rhyodacites, besides fine and conglomeratic sandstone and alluvial deposits. The density of the intermediate acid rocks averages 2.61 g/cm^3. Such units were not individualized as a gravimetric domain in this work having only been observed in the geologic map.

Domain 4 – Center-South Portion

The domain D4 includes lithotypes from the Sul-Rio-Grandense Shield and from the Cenozoic sedimentary deposits with gravimetric anomalies, which represent sources associated to complex geologic units, with granitoid intrusions and sedimentary basins (CPRM, 2008). Such complexity is expressed by the density and depth variation of the rocks, producing significant differences in the values of the gravimetric anomalies. The range of anomaly value for this geophysical domain is one of the most expressive, varying from –10 to 51 mGal.

The coastal plain of the State corresponds to a region where are exposed the most superficial and proximal deposits of the sedimentary package accumulated in the Pelotas Basin (CPRM, 2008). It developed over a basement formed by the complex crystalline Precambrian and by the sedimentary and volcanic sequences from Paleozoic and Mesozoic of the Paraná Basin. The positive gravimetric anomalies found in this domain have large amplitude and are possibly associated to the crystalline basement and dikes originated from the fissural volcanism associated to the rift phase of the Pelotas Basin (Rolim et al., 2008; Holz et al., 2009).

CONCLUSIONS

The use of the three methods based on residuals of altimetric, gravimetric and Bouguer anomaly aimed to filter the discrepant observations of the database to providing a better interpretation of the results and allowing a gravimetric characterization of the RS. By establishing the upper and lower thresholds for the calculation of residuals allowed the elimination of discrepant points in each method, where it was possible cross checking and to eliminate suspicious observations of gross errors with coincident positioning for at least two methods.

The Bouguer anomaly map that was generated after removal of the gross errors presented an excellent correlation with the main geologic units of the RS. Four geophysical domains were identified: D1 and D2, associated to the basic and acid volcanism of the Paraná Province; D3 associated to the intermediate to acid volcanism of the southwest portion of the State; and D4 associated to the units of the Sul-Rio-Grandense Shield and to Cenozoic sedimentary deposits.

The small number of detected errors is a positive result since this demonstrates the quality of the database of the land gravimetric surveys performed since the 1950 decade in the Rio Grande do Sul State. This does not preclude the existence of localized errors and it is suggested future studies with the aid of the gravimetric and digital elevation models generated by orbital platforms.

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