REVISTA ÁGUAS SUBTERRÂNEAS

Artigos

Compartmentation in the Guarani Aquifer System northeastern region of the Rio Grande do Sul State

Compartimentação do Sistema Aquífero Guarani na região nordeste do Estado do Rio Grande do Sul

Alex Bortolon de Matos[1]; Pedro Antonio Roehe Reginato[2]; Gustavo Barbosa Athayde[3]✉

[1] Universidade Federal de Roraima (UFRR), Roraima, RR.
[2] Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, RS.
[3] Universidade Federal do Paraná (UFPR), Curitiba, PR.

✉ alexbortolon@gmail.com, pedro.reginato@ufrgs.br, gustavo.athayde@ufpr.br

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Abstract

This study aims to evaluate the structural compartmentation of the Guarani Aquifer System (GAS) in the northeastern region of the Rio Grande do Sul (RS) state. For this purpose, an integrated analysis of 747 morphostructural lineaments identified in the scale 1:1,000,000 with geometry features and potentiometry of the GAS was performed. Based on this evaluation, a main set of structures, N30W and N60E oriented, responsible for the GAS compartmentation within the study area, was identified. These directions are related to the main tectonic structures that originated from the basement of the Paraná Basin, which could indicate that these identified structures are part of large fault systems in this region. The variations in the GAS potentiometry and altimetry of the top related to the compartmentation show the existence of several blocks formed under the influence of NW and NE structures located mainly in the large valleys, which sometimes work as a discharge zone of the aquifer. According to the analysis, the GAS in the northeastern region of RS seems to be divided into compartments of different sizes. This structural and geometrical framework imposed by tectonic structures influences the GAS potentiometry and flow dynamics.

Palavras-chave:

Sistema Aquífero Guarani.
Compartimentação.
Lineamentos Morfoestruturais.

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Resumo

O objetivo deste estudo foi avaliar a compartimentação estrutural do Sistema Aquífero Guarani (SAG) na região nordeste do Rio Grande do Sul (RS). Para tanto, foi realizada uma análise integrada das informações de 747 lineamentos morfoestruturais identificados na escala 1:1.000.000 com as características geométricas e potenciométricas do SAG. Com base nessa avaliação foi identificado um grupo principal de estruturas, com orientações N30W e N60E, que são as principais responsáveis pela compartimentação do SAG na região. Essas orientações estão relacionadas com as principais estruturas tectônicas originadas no embasamento da Bacia do Paraná, o que pode indicar que as estruturas identificadas neste estudo podem ser parte de um grande sistema de falhas existente na região. As variações observadas no topo e na potenciometria do SAG relacionadas à compartimentação mostram a existência de vários blocos, que são formados sob influência das estruturas NW e NE, localizadas principalmente nos grandes vales, e que em alguns casos funcionam como zonas de descarga do aquífero. Assim, com base nas análises desenvolvidas, o SAG na região nordeste do RS se encontra dividido em compartimentos de diferentes portes. O arcabouço estrutural gerado pela ação das estruturas tectônicas tende a influenciar tanto na potenciometria, quanto na dinâmica do fluxo de água subterrânea do SAG.

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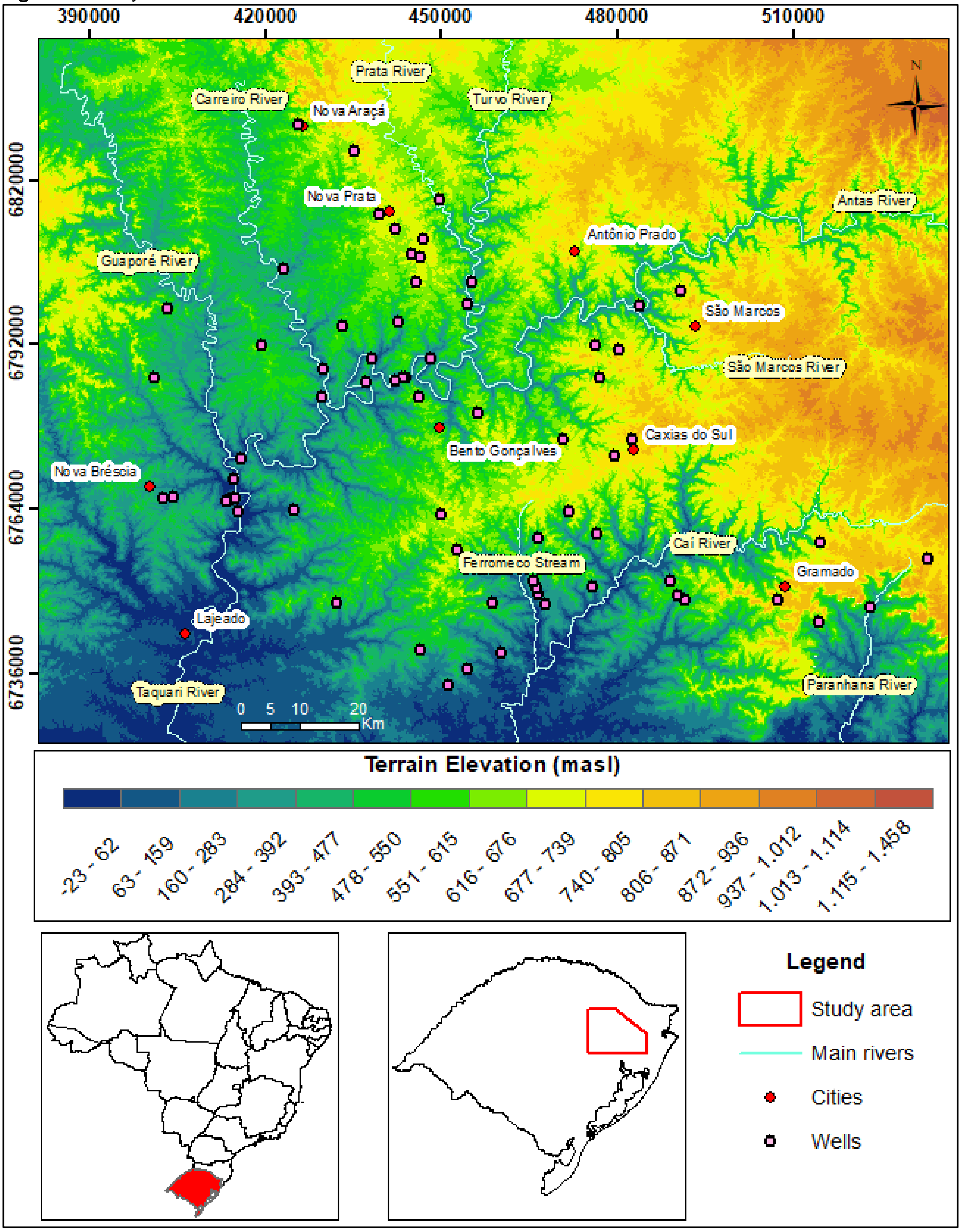
1. INTRODUCTION

In the northeastern region of Rio Grande do Sul state (RS), located in the southern part of Brazil, there are quantitative and qualitative limitations regarding the use of surface water resources. These limitations have provided an increase in the use of groundwater in recent years with the exploitation of this resource occurs many times without due knowledge about its characteristics, which can damage the system.

The study area is in the Geomorphological Domain Planalto dos Campos Gerais in the northeastern region of RS and between the coordinates UTM south 6852005 and 6719710 and UTM east 371744 and 547243 (Figure 1).

Figure 1 – Study area location



The Guarani Aquifer System (GAS) is one of the main water reservoirs in the world, occupying an area of 1,087,000 km² in the territories of Brazil, Uruguay, Argentina, and Paraguay. Despite being presented in its initial conception as a regionally homogeneous system, Hausmann (1995), Rosa Filho *et al.* (2003), Machado (2005), Soares *et al.* (2008), Giardin and Faccini (2011), among others, showed in the last decades that the GAS present great variability in its characteristics.

In the northeastern region of RS, the GAS is characterized by granular aquifers ranging from unconfined to confined, which according to Machado (2005) and Giardin and Faccini (2011) belong to different Hydrostratigraphic Units (Botucatu, Pirambóia, Passo das Tropas, Alemoa, and Sanga do Cabral) and is limited at the top in almost all the area by volcanic rocks of the Serra Geral Group.

According to Araújo *et al.* (1995), the structural behavior of the GAS was controlled by several factors, such as the activation of fault systems, uplifting of the edges of the Basin, activation of the arches, and volcanic processes that originated the rocks belonging to the Serra Geral Group. These structures, which can be observed throughout the entire Paraná Basin, are closely related to basement tectonic structures. The main tectonic directions seemed to be NE and NW complemented by the ductile shear zones occurring mainly in the N60-70E orientation and a system of fractures lying along with the N20-50W orientation (ZALÁN *et al.*, 1987; ZALÁN *et al.*, 1990; MILANI *et al.*, 1998; TRENTIN and ROBAINA, 2006).

Many of these tectonic structures can be identified on the surface as a linear feature which should be in these cases considered as a morphostructure and not a lithostructure (O'LEARY *et al.*, 1976; LISBOA, 1996).

Tectonic structures can be responsible for some level of aquifer compartmentation in the Paraná Basin. The larger faults can cause vertical movements in the blocks, creating variations in the rock packages which sometimes can influence the groundwater flow. Several authors who worked on and systematized geological data from the Paraná Basin suggested this behavior. Soares *et al.* (2007), for example, used the main tectonic lineaments, the structural contour of the GAS, and the thickness variation of the Botucatu and Pirambóia Formations to evaluate the structural compartmentation of the Paraná Basin. According to the authors, an array of blocks was built and led to interference in the water flow between areas. Machado (2005) launched the hypothesis that the Terra de Areia-Posadas (TA-PFS), Jaguari-Mata (JMFS), and Dorsal de Canguçu (DCFS) Fault Systems were responsible for the development of four GAS compartments with different characteristics in RS. Several other studies showed how the structures had determined block formation and large vertical displacements with groundwater flow interference (HINDI, 2007; GIARDIN; FACCINI, 2011; PHILIPP *et al.*, 2014; GASTMANS *et al.*, 2017).

The main goal of this study is to evaluate the compartmentation of the GAS in the northeastern region of RS based on the analysis of morphostructural lineaments and variations of the GAS geometry and potentiometry.

2. METHODOLOGY

A database with 68 water wells (with depths ranging from 126 to 2,251 m) drilled across the volcanic sheets inside the GAS sedimentary rocks was considered. Another well (S36), different from the others, was drilled only in the volcanic rocks without intercepting any sedimentary layer. All the data were obtained from the Groundwater Information System (SIAGAS) of the Geological Survey of Brazil (SGB-CPRM), reports from the Riograndense Sanitation Company (CORSAN), and drilling reports from private companies. For every single well, information about the construction profile, lithologies intercepted in the drilling, terrain elevation, and water level (only at 38 wells) was recorded.

The method used to identify the compartmentation of the GAS was based on the tracing of the morphostructural lineaments and the spatial variation in the GAS geometry and potentiometry.

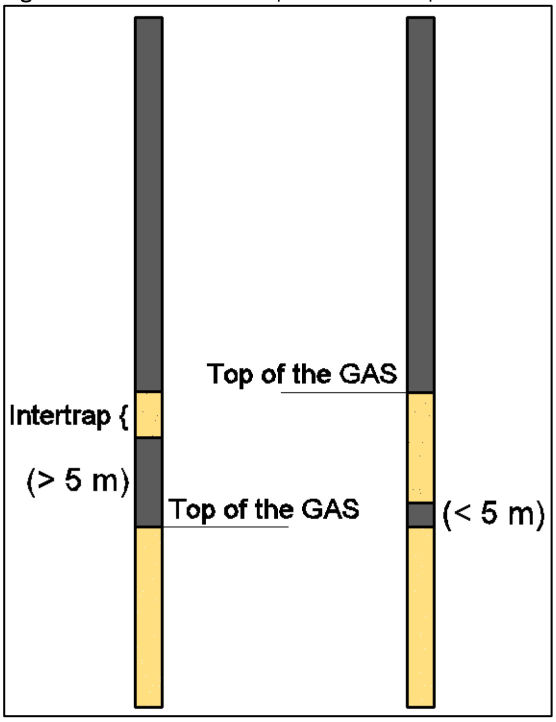
The lineament extraction was conducted in images of digital elevation models (DEM) obtained from the SRTM bearing 30 m resolution, and a wider area was selected to minimize edge effects. Visualization and tracing techniques were enhanced by false illumination procedures in the 0°, 45°, 90°, and 315° directions.

The lineaments were traced on a scale of 1:1,000,000 in the ArcGIS software where vector layers were created with information of the start and end points, allowing for the development of Rose diagrams according to the method proposed by Queiroz *et al.* (2014).

The top of the GAS was obtained by considering the difference between the terrain elevation and the depth of contact between the volcanic and sedimentary rocks. In cases where intertraps have been identified, the top of the GAS was determined using the following rule: i) when the volcanic rock thickness below the sedimentary rock layer was higher than 5 m, the contact below was considered as the top of the GAS; ii) in cases where the thickness was lower than 5 m, the top of the GAS was considered as the upper contact of the sedimentary rock that is above it (Figure 2).

The potentiometry was obtained from information on the static levels identified for each well. The potentiometric surface at each point was the difference between the terrain elevation and the depth to the static level. It is important to mention that some visual distortions in the potentiometric surface may occur because of the number of samples and their distribution in the region.

Figure 2 – Schematics for the position of the top of the GAS



The starting point to evaluate how the structures work in the compartmentation of the GAS was the analysis of the correlation between the identified lineaments and the spatial variability of the GAS geometry and potentiometry. For this purpose, representative profiles based on the well's information were used to identify the existence of significant variations related to the lineaments that can explain their influence on the movement of rock packages and in the groundwater flow.

3. RESULTS AND DISCUSSION

3.1. Evaluation of morphostructural lineaments

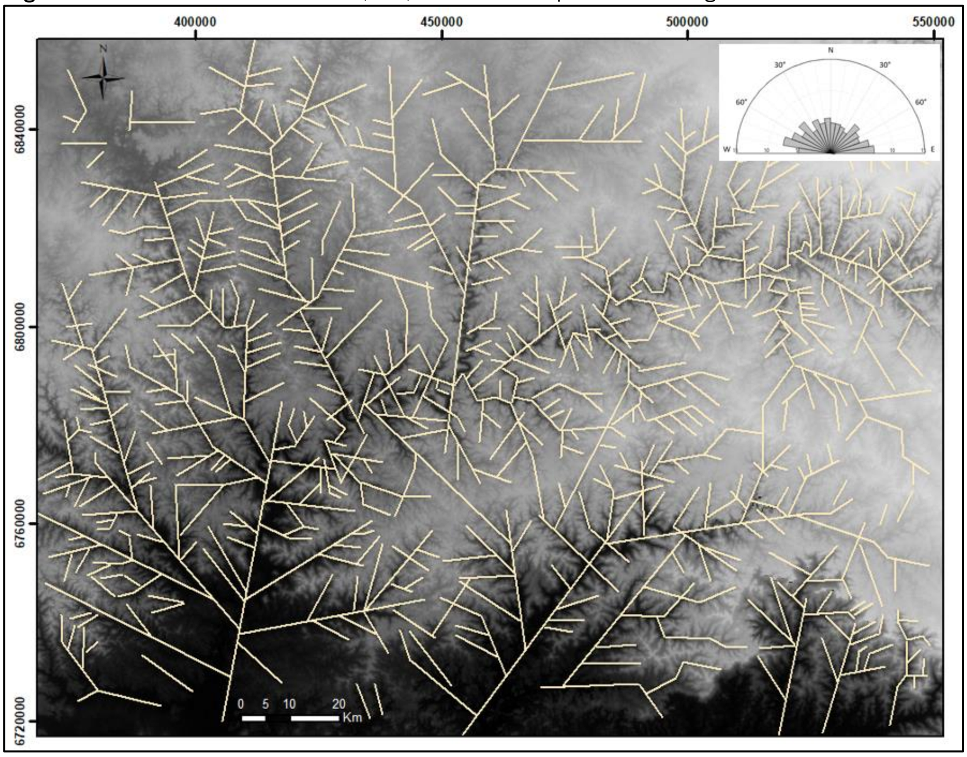
Throughout the lineament extraction method, 747 morphostructural lineaments were identified for the scale of 1:1,000,000 in the study area. The lineament lengths reached up to 66 km and the preferential directions were N50W, N60-80W, N50E, N80E, and E W and secondary N-S and N30W (Figure 3). Table 1 presents the characteristics of the lineament lengths.

Some lineaments seemed to be closely related to large regional tectonic structures of the sedimentary Paraná Basin that were described by authors such as Picada (1971), Fernandes et al. (1993), Machado (2005), Giardin and Faccini (2010), and Philipp et al. (2014). The lineaments with NW orientation are linked to the Terra de Areias-Posadas (TA-PFS) and Torres Posadas (TPFS) Fault Systems. On the other hand, the NE lineaments may be related to the Blumenau/Soledade Fault Zone, Dorsal de Canguçu Fault System (DCFS), and Antas River Lineament (ARL). For Reginato and Strieder (2006), the E-W and N-S lineaments correspond to two important fields of tension efforts, which according to Zalán et al. (1990) is related to the separation process between South America and Africa.

Table 1 – Descriptive statistics of the lineament lengths (m)

Maximum	65,901.10
Minimum	1,314.89
Mean	7,802.93
Median	6,120.73
Standard deviation	6,518.32

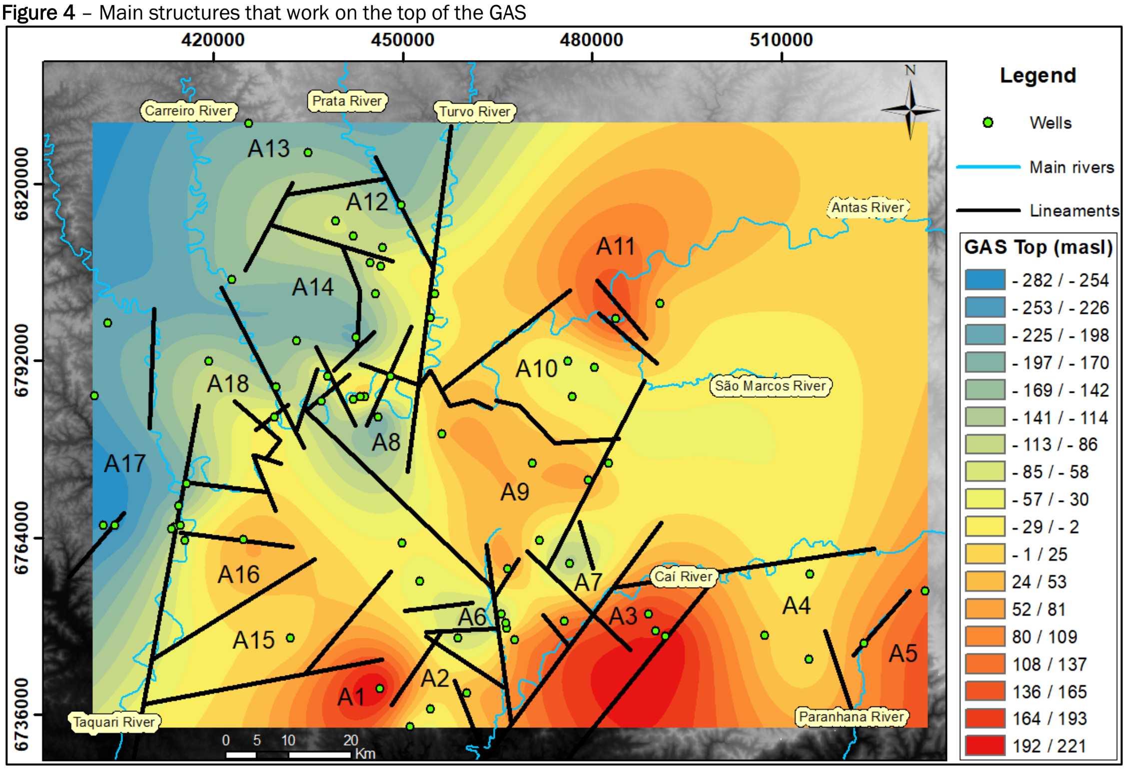
Figure 3 – Lineaments for the scale 1:1,000,000 and the respective Rose diagram



3.1. Geometric features of the GAS

The lineaments traced on the scale 1:1,000,000 were plotted over the map that represents the top of the GAS to verify which of them could explain geometric features of the GAS in the area (Figure 4). Thus, those lineaments between the transition regions of uplifted and lower elevations of the top and which could work to form structural blocks were highlighted.

Figure 4 – Main structures that work on the top of the GAS



Areas A1, A3, and A5 in the southern part of the study area, close to the escarpment border, represent blocks where the top of the GAS are quite high compared to the two areas between them (A2 and A4). This feature shows a decreasing trend of the position of the GAS top towards the valleys, which is a behavior already o bserved by Matos *et al.* (2018) in the escarpment border of the northeastern region of RS.

In the central part of the studied region, areas A6, A7, and A8 represent lower blocks. At first, it seems that these three areas are related but the existence of large structures that also affect other areas and the different levels of depth of the GAS top indicate that they are distinct lower areas and not a single large lower block.

Areas A9 and A11 correspond to blocks with GAS top elevated in the topography. They are separated from each other by a lower block (A10). It may be possible that the tectonic structures in the Antas River Valley are imposing the variation of the top of the GAS between these three areas (A9, A10, and A11) and the region close to the Turvo and Prata River Valleys.

There are several smaller structures within the Antas River Valley to which block formation can be attributed. It is worth to mention that there is an uplifted block (between A8 and A14) in the river channel and a lower block (A8) in the area with the highest terrain elevation at the top of the hill. This is important because it shows that lower blocks are not necessarily positioned in the areas close to the valleys, reinforcing the existence of strong structural influences. In the northern region of the study area, the same pattern of the uplifted block (A12) between two low blocks (A13 and A14) can be observed.

In the Taquari River area, the same trend marked by a decreesing gradient of the topographic elevation of the GAS top can be seen following from two uplifted blocks (A15 and A16). The N11E structure inserted in this valley may represent an important border feature for the GAS, which presents increasingly negative values towards the west (A17).

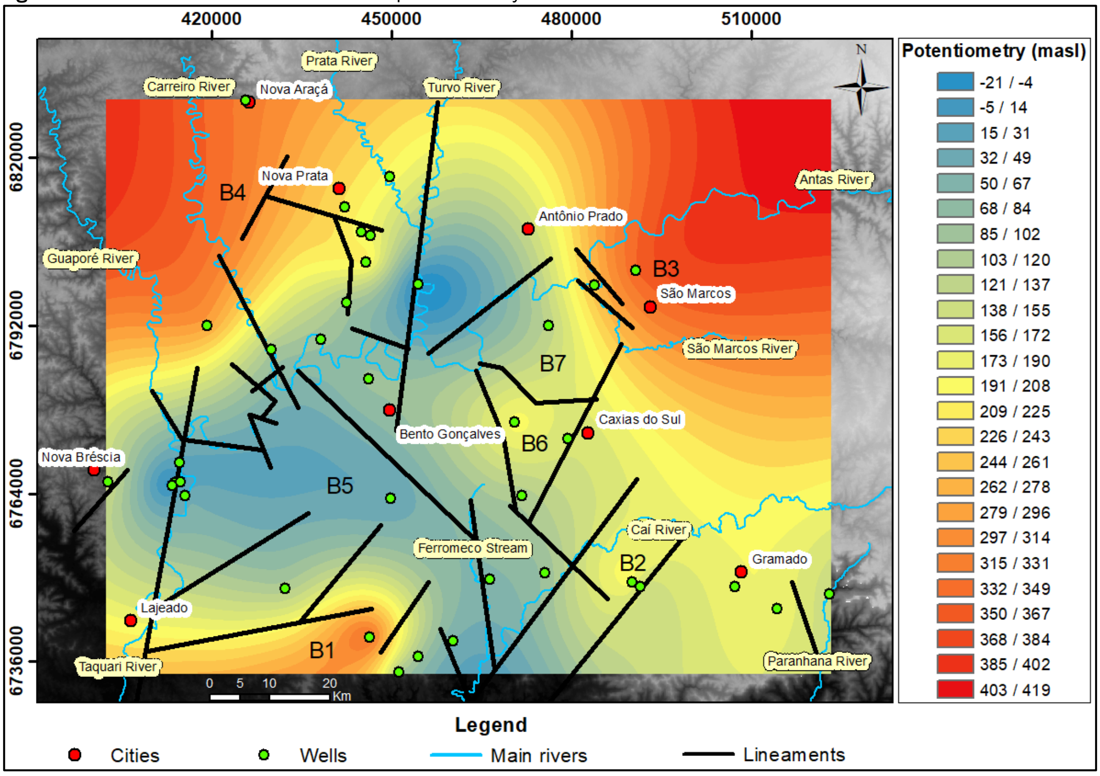
Despite being composed of negative elevation values of the GAS top, the area A18 can be considered an uplifted tectonic block considering the three lower blocks that limit it (A8, A14, and A17).

Through the analysis of the geometric features of the GAS, the pattern of block formation, which alternates between uplifted and lower portions, was noted. The structure of these patterns has a strong relationship with the tectonic process which could be reflected in the morphostructural lineaments identified in the area.

3.3. Tectonic implications in GAS potentiometry

The influence of the structures in the GAS potentiometry was evaluated after two distinct approaches: i) the existence of structures that could be responsible for significant potentiometric "breaks", as a large potentiometric variation between areas compared to the distance between them, and ii) the presence of structures positioned in low potentiometric areas that could function as a discharge zone of the GAS (Figure 5).

Figure 5 – Main structures that work on the potentiometry of the GAS



In the southern portion of the study area, it was verified two important high potentiometric areas (B1 and B2) separated by a lower potentiometric area where the Caí River and Ferromeco Stream Valley are located. Regionally, the flow follows these high potentiometric areas towards the valleys, which are possibly functioning as a discharge zone for the GAS.

In the north, it was verified flows from the highest potentiometries in B3 and B4 towards the Prata River Valley in the section positioned after its confluence with the Turvo River where the GAS potentiometry is at least 250 m below the water level of the river. It is important to point out the existence of distortions in the interpolation of the values due to how the wells are dispersed in the area, as for example with the Prata River where, although it seems that the entire flow goes to only one point, in reality, it shows that the flow goes towards the river channel.

In the Antas and Carreiro River Valleys region, the potentiometry is close to the water level of the rivers, showing that this area may function as a discharge zone. A similar situation also occurs in the Taquari River Valley, where an N11E structure was identified and the potentiometry is lower than in the adjacent areas with flow toward this region.

The B5 area stands out for its peculiar characteristic, and despite its lower potentiometry, this area is topographically elevated and far from the valleys of the region.

In the northeastern portion, it was verified the presence of two areas with high potentiometry (B3 and B6) interspersed by area B7 with lower potentiometry. The presence of sets of structures in this region shows the formation of blocks with different potentiometric characteristics.

The configuration of the potentiometry in the areas shows that the tectonic processes may be directly responsible for the compartmentation of the GAS and patterns of groundwater flows.

3.4. Main structures that influence in the compartmentation of the GAS

The definition of the main structures that influence the compartmentation of the GAS considers, as a predominant factor, the variations of the top of the GAS with the potentiometry being used in a complementary way. Thus, the action of 61 structures is the main responsible for the movement of blocks that sometimes are so intense that can influence the potentiometry between areas. Figure 6 shows the main structures identified in the study area and the profiles used. Figures 7, 8, and 9 show the profiles information used to detail the GAS compartmentation processes in the region.

Figure 6 – Main structures that influence in the compartmentation of the GAS, the respective Rose diagram and the profiles used

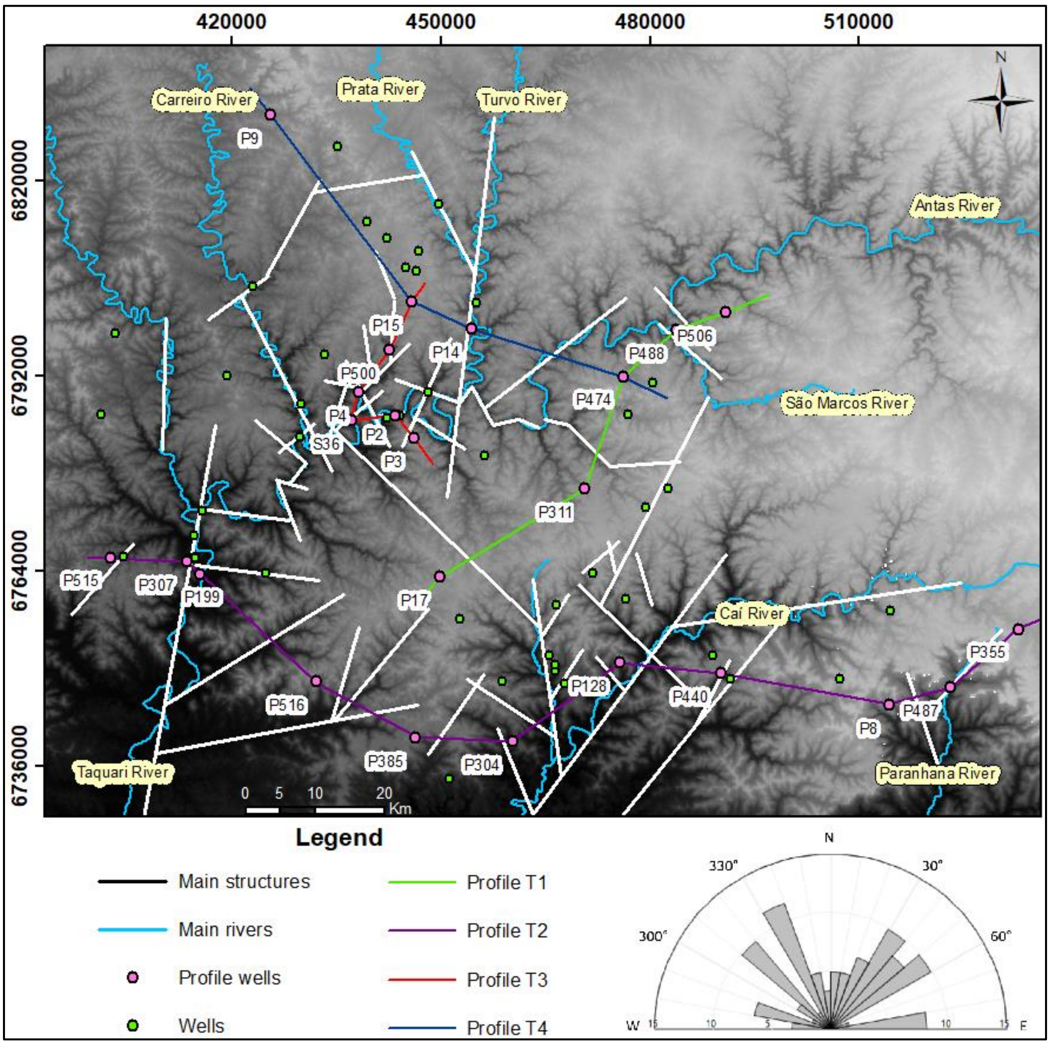
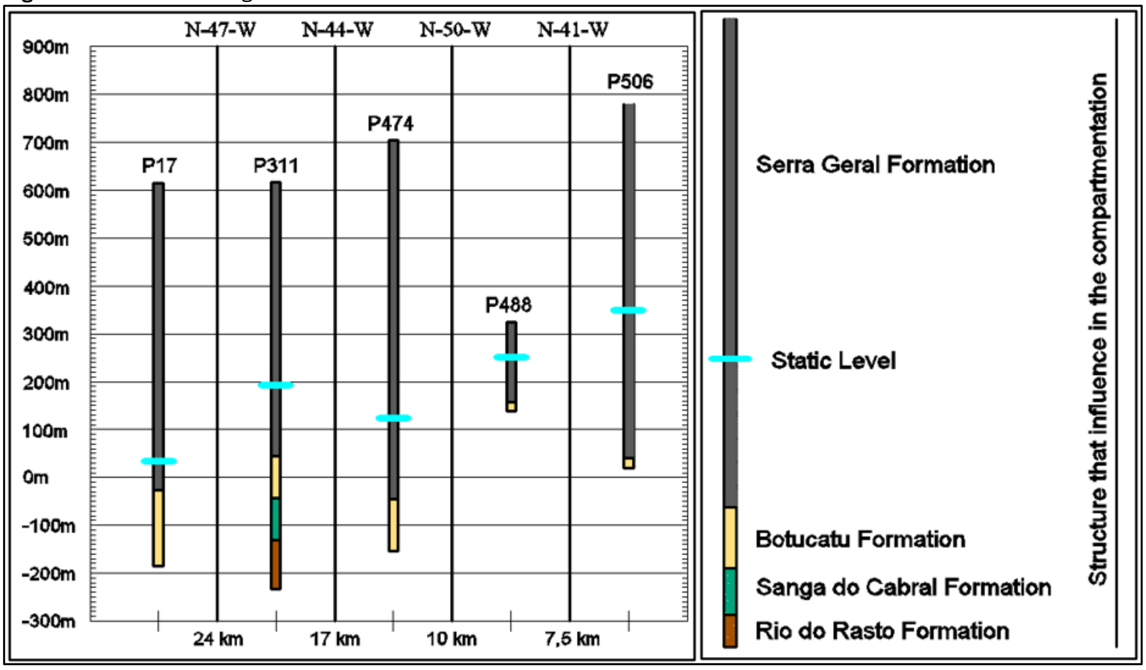


Figure 7 – Profiles referring to T1 and main characteristics evaluated



Profile T1 covers the central portion of the study area and reveals the importance of four NW structures to the variations of the top and the potentiometry of the GAS, being responsible for the formation of tectonic blocks in the region.

Profile T2 crosses the southern portion where large structures are located in the Caí and Taquari River Valleys. From these profiles, it was verified that the top of the GAS alternates between higher and lower points, being these last ones positioned mainly close to the valleys.

Figure 8 – Profiles referring to T2

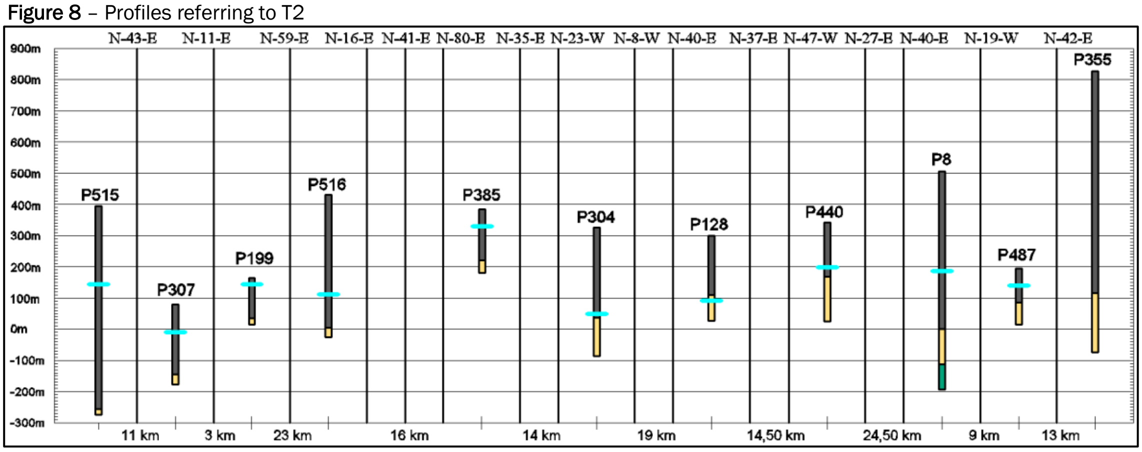
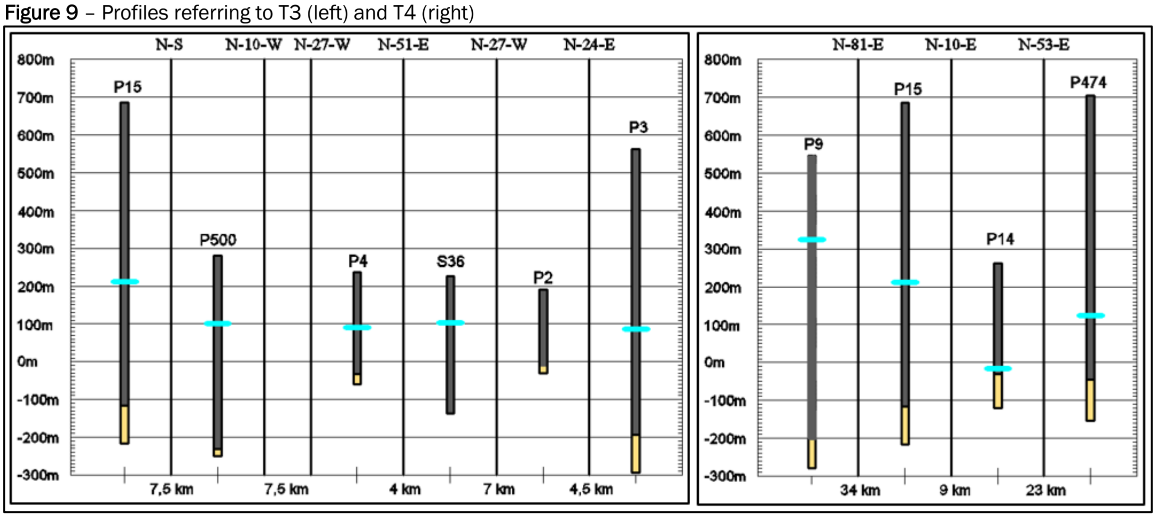


Figure 9 – Profiles referring to T3 (left) and T4 (right)



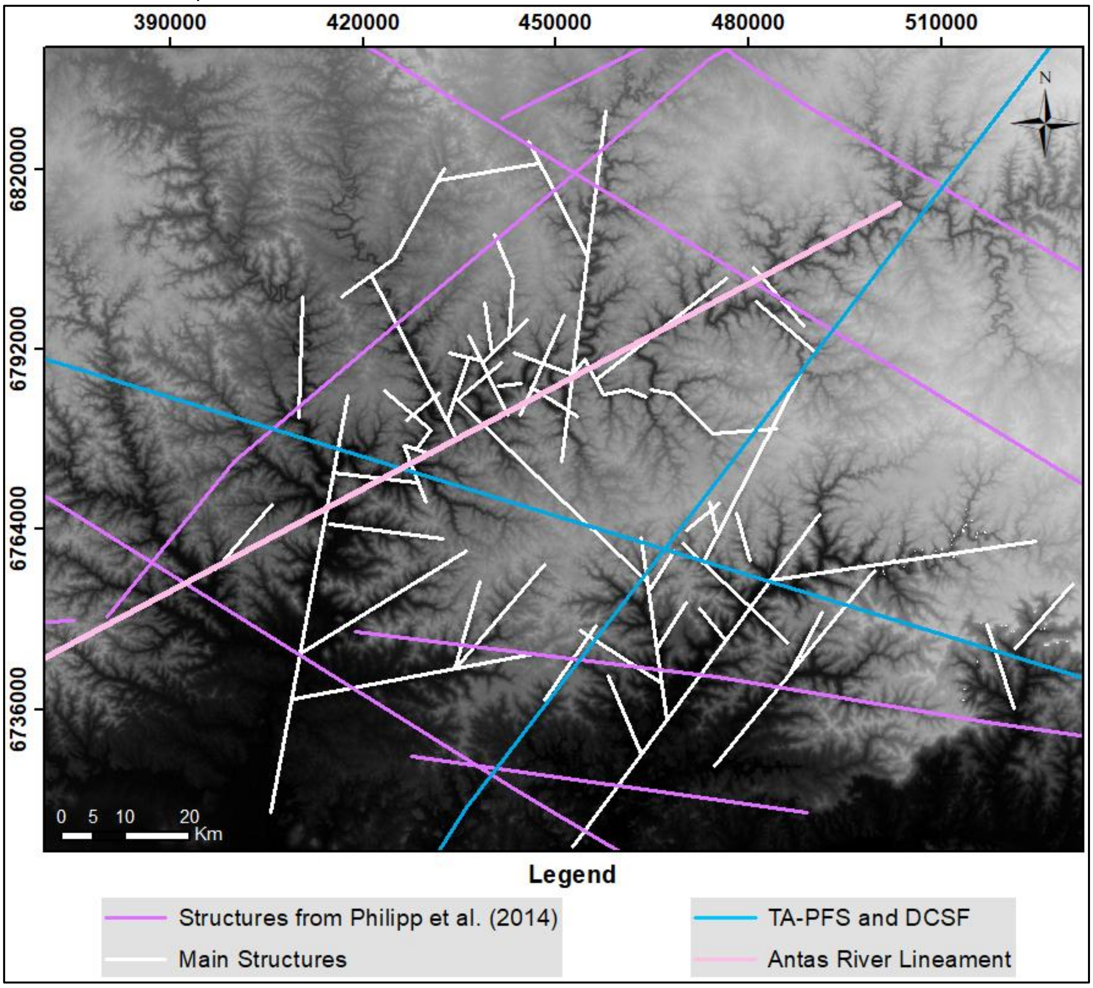
The information from profile T3 highlights the structural behavior in the Antas River Valley and shows the existence of significant variations at the top of the GAS even with a short distance between the areas where the analyzed wells are located, showing a strong structural action in the area. Despite this, there was minor variation in the potentiometry with the values being close to the river levels.

Profile T4 shows that, despite the variations in the top of the GAS, significant differences in the potentiometry values between the areas, caused mainly by the action of three NE oriented structures, stand out.

The morphostructures identified, even the smaller ones, can be associated with the action of larger tectonic structures such as faults and fault systems, as in the case of the Antas River Lineament described by Giardin and Faccini (2010), which has a N65E orientation, and the Dorsal de Canguçu and Terra de Areia-Posadas Fault Systems with NE and NW orientations, respectively (Figure 10).

Considering only the structures that work in the compartmentation of the GAS, it was verified that they present main orientations N30W and N60E, and secondary N50W, N40-50E, and E-W. These orientations reflect the characteristics of the basement main alignments in terms of ductile shear zones and fracturing systems mentioned by Zalán *et al.* (1987) and verified throughout the entire Paraná Basin.

Figure 10 – Relation between the main structures that work in the compartmentation of the GAS in the region and the structures described by other authors



4. CONCLUSIONS

The present paper proposed an integrated analysis of morphostructural lineaments using data from the top and the potentiometry of the GAS, making possible the identification of tectonic compartmentation of the GAS in the region and revealing some important processes that may also occur in other regions of the Paraná Basin.

Most of the morphostructural lineaments identified presented orientations N60-80W, N50W, N50E, N80E, E-W, and secondary N-S and N30W. Considering only those that work in the compartmentation of the GAS, it was verified the main orientations N30W and N60E and secondary N50W, N40-50E, and E-W. These orientations reflected, in part, the characteristics of the alignments originated from the basement of the Paraná Basin, and showed that these identified lineaments can be representations in the scale of detail of pre-existing fault systems that were reactivated during the geological evolution of the region.

The variations observed at the top and in the potentiometry of the GAS and also related to structural compartmentation showed the existence of several uplifted and lowered tectonic blocks that alternate over the entire study area.

The profiles' information showed the importance of the NE and NW structures in the GAS scenario. In the central portion, there is a strong action of NW structures both in the top and potentiometry of the GAS, while in the north NE structures are responsible for variations in potentiometry that reached over 100 m. Furthermore, in the southern portion and Antas River Valley region, the valleys where large structures were identified functioned as a discharge zone of the GAS.

Different from the Prata and Turvo River Valleys, in the region close to the Antas, Taquari, and Carreiro River Valleys, the potentiometry was close to the water level of the rivers, showing that this area may function as a discharge zone. To verify this process, some hydrogram separation techniques could be applied in further studies.

5. ACKNOWLEDGEMENTS

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