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CONNECTIVITY AND MAGNETIC-STRUCTURAL COMPARTMENTALIZATION OF THE SERRA GERAL AND GUARANI AQUIFER SYSTEMS IN CENTRAL STATE OF PARANÁ (PARANÁ BASIN, BRAZIL)

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ABSTRACT. Recent research projects on the Guarani Aquifer System (GAS-granular), Paraná Basin, Brazil, have been evaluating the tectonic control and its hydrogeological potential, flow patterns, chemical properties and environmental protection aspects. One of this projects is the present research that has investigated a structured area in central State of Paraná of about 23,000 km^2, delimited by coordinates 24°00'S and 25°00'S, 51°00'W and 53°00'W. The study involves Geographic Information System (GIS) integration of aeromagnetic, geological and structural characterization of lineaments based on Digital Elevation Model (DEM) and Landsat images, hydrogeological and hydrochemical data. Basaltic flows and diabase dikes (NW-SE) of the Serra Geral Formation (Lower Cretaceous) predominate in the studied area. These rocks correspond to the overlying Serra Geral Aquifer System (SGAS-fractured). The purpose of the study is to investigate the structural control on both flow and chemism of SGAS groundwater and also to identify fractures that might represent hydraulic connectivity zones to the underlying GAS. Processing and interpretation of aeromagnetic data using various techniques, useful for enhancing shallow sources, and integration with further remote sensing and geological data, allowed to outline the regional structural framework, which is characterized by a mosaic of tectonic blocks delimited by NW-SE (diabase dykes) and NE-SW (Paraná Basin basement) structures. This magnetic-structural framework was compared with the spatial distribution of hydrogeological and hydrochemical parameters. The integrated interpretations made it possible to recognize the structural control on hydrogeology and hydrochemistry of the SGAS and SAG. The results, presented in a georeferenced map, show the main zones of confinement and/or connection of SGAS and GAS.

Keywords: Guarani Aquifer System, Serra Geral Aquifer System, Paraná Basin, hydraulic connection, aeromagnetometry.

RESUMO. Projetos recentes de pesquisa no Sistema Aquífero Guarani (SAG-granular), Bacia do Paraná, Brasil, têm avaliado o controle tectônico e seu potencial hidrogeológico, padrões de fluxo, propriedades químicas e aspectos de proteção ambiental. Um destes projetos é a presente pesquisa, a qual investigou uma área estruturada na região central do Estado do Paraná, delimitada pelas coordenadas 24°00'S e 25°00'S, 51°00'W e 53°00'W, com aproximadamente 23.000 km^2. O estudo envolve integrações em Sistema de Informações Geográficas (SIG) de dados aeromagnéticos, geológicos, estruturais Modelo Digital de Elevação (MDE) e imagens Landsat, hidrogeológicos e hidroquímicos. Lavas basálticas e diques de diabásio (NW-SE) da Formação Serra Geral (Cretáceo Inferior) predominam na área estudada. Estas rochas correspondem ao Sistema Aquífero Serra Geral (SASG-fraturado), sobrejacente. O objetivo do estudo é investigar o controle estrutural do fluxo e do quimismo das águas subterrâneas do SASG e identificar também fraturas que possam representar zonas de conexão hidráulica com o SAG subjacente. Processamentos e interpretações de dados aeromagnéticos, a partir de várias técnicas, e a integração com dados de outros sensores remotos e geológicos permitiram a composição de um arcabouço estrutural regional, o qual é caracterizado por um mosaico de blocos tectônicos limitados por estruturas NW-SE (diques de diabásio) e NE-SW (embasamento da Bacia do Paraná). Este novo arcabouço magnético-estrutural foi comparado com a distribuição espacial dos parâmetros hidrogeológicos e hidroquímicos. A interpretação integrada permitiu reconhecer o controle estrutural da hidrogeologia/hidroquímica dos SASG e SAG. Os resultados, apresentados em um mapa georreferenciado, mostram as principais zonas de confinamento e/ou conexão dos SASG e SAG.

Palavras-chave: Sistema Aquífero Guarani, Sistema Aquífero Serra Geral, Bacia do Paraná, conexão hidráulica, aeromagnetometria.

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INTRODUCTION

The Laboratory for Research in Applied Geophysics, Department of Geology, Universidade Federal do Paraná, has recently conducted hydrogeophysical research on the Serra Geral Aquifer System (SGAS), in the State of Paraná, seeking to evaluate its magnetic and structural compartmentalization in relation to the hydraulic connectivity to the Guarani Aquifer System (GAS) and other underlying aquifers. This study is part of a hydrogeological research project proposition in the Paraná Basin (Rosa Filho, et al., 2003), whose main focus is to evaluate the potential, flow, chemism and environmental protection of GAS, based on the structural framework and previous relevant studies (e.g. Portela Filho, 2003; Ferreira, 2005; Ferreira et al., 2005; Portela Filho et al., 2005; Mocellin & Ferreira, 2009; Bongiolo et al., 2011).

This work is the result of the project “Connectivity and structural-magnetic compartmentalization of the Serra Geral and Guarani aquifer systems in the central region in the State of Paraná” (Ferreira, 2005), whose location is indicated in Figure 1, and is based on the integration of aeromagnetic, geological, topographical, hydrological and hydrochemical data, in Geographic Information System (GIS) environment.

Regarded as one of the largest groundwater reservoirs in the world, the GAS involves rocks of the Triassic and Jurassic, in a total area of approximately 1,200,000 km^2, in Brazil and neighboring countries like Uruguay, Paraguay and Argentina (Araújo et al., 1995). This aquifer system underlies the set of magmatic rocks (mainly basalts and diabase dikes), which constitute SGAS.

The GAS has a significant volume, estimated at 46,000 km^3, and recharge rates and renewal time which enable to extract flows from a few hundred to 1,000-2,000 m^3/h, but presents peculiar hydraulic behavior in confined situations, reflecting the structural heterogeneities of Paraná and Chaco-Paraná basins (Ferreira, 1982a,b; Zalán et al., 1990). According to studies carried out in the State of Paraná, the location of the potentiometric surface of granular reservoirs implies that the volcanic rocks of the Serra Geral Formation (SGAS) act as reservoirs, as well as hydraulic barriers. Thus, the fractured basalt aquifers should be considered, at least partly, as components of the same hydrogeological system, due to the probable connection to the granular aquifer and the similarity of some flow patterns.

With respect to the control exercised by the uplifts, it is noteworthy that there are swarms of diabase dikes (NW-SE) occurring along the Ponta Grossa Arch (Ferreira, 1982a,b). The dikes play a key role in the partitioning of the GAS and large compartments. According to Araújo et al. (1995), these compartments have different hydrological regimes, leading to a segmentation of the flow pattern of the recharge areas. The regional flow gradient is modified by local discharges induced by the intersection of regional faults and dike swarms. The mix of flows of the fractured SGAS and granular SAG waters was observed in previous studies (e.g. Bittencourt, 1978; Fraga, 1986, 1992; Rosa Filho et al., 1987; Buchmann, 2002; Bittencourt et al., 2003; Portela Filho, 2003; Ferreira, 2005; Ferreira et al., 2005; Portela Filho et al., 2005; Bongiolo, 2007; Mocellin & Ferreira, 2009; Bongiolo et al., 2011). Thus, it is very important to understand this process of water mix and locate the intermediate discharge zones, mainly in the Brazilian territory.

Therefore, the development of hydrogeological and exploration models for GAS should focus on structural aspects and their relationship with recharge and discharge areas. Based on this assumption, it is essential to establish an exploration strategy that involves socioeconomic, technical and scientific factors (geological, geophysical, hydrogeological and hydrochemical), which make it possible to locate the most favorable sites for extraction and exploitation of underground water, while adopting management practices that reconcile such exploitation with environmental protection and GAS sustainability.

The delineation of structural magnetic compartmentalization is, therefore, imperative for the advancement of GAS knowledge, given its hydraulic connection with SGAS. Therefore, this research is focused on the study of SGAS and the role played by the structures on the hydraulic flow from SGAS and from underlying granular aquifers such as the GAS. According to evidence provided by the aforementioned literature, the compartmentalization of both aquifer systems points to a varied degree of isolation of their waters, physical flow barriers in GAS, and connectivity with SGAS by vertical flow through fractures, aspects that will be detailed here.

METHODS

The determination of the structural framework of the area was based on two research levels. To generate the surface model of the basalts, thematic maps of Soares et al. (1982) and Zalán et al. (1987) were used, in which the occurrence of large lineaments were described and interpreted. These maps were the basis for the composition of the surface structural framework. LinAnalyst software (Freitas, 2005) was used to interpret the structural lineaments outlined from Landsat 7/ETM$^+$ images, digital elevation model (90 m cell data from the SRTM sensor – Shuttle Radar Topography Mission – NASA) and morphological and structural analysis of the drainage network.

The subsurface structural map was based on the processing and interpretation of aeromagnetic data from the Rio Iguaçu

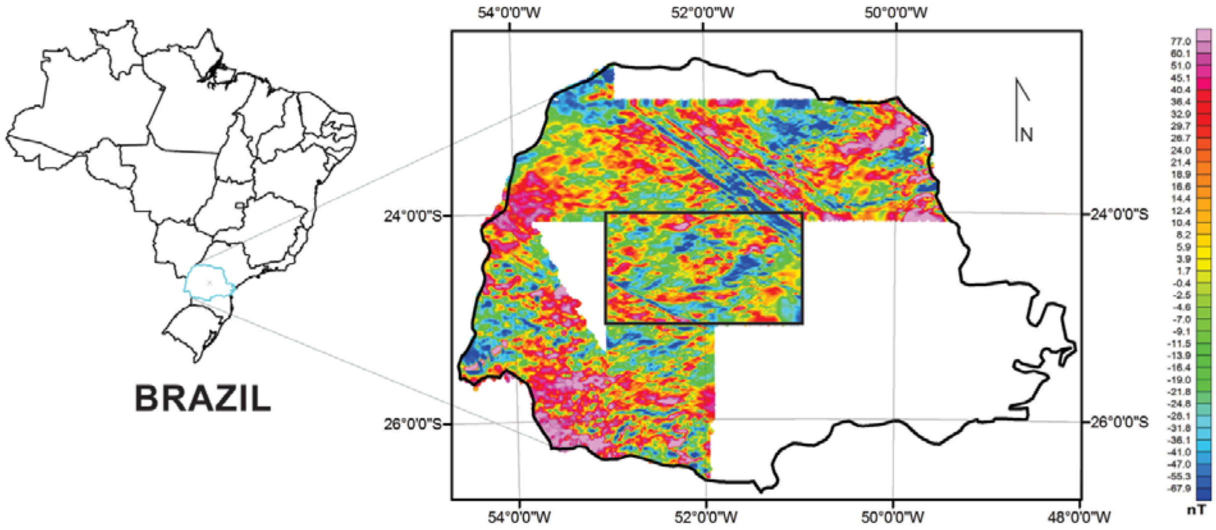

Figure 1 – Location of the study area (red) in the partial aeromagnetic map from the State of Paraná. 1 – Pre-Cambrian basement, 2 – Paleozoic sedimentary rocks, 3 – Serra Geral Formation (Lower Cretaceous – basalts and dikes), 4 – Caiuá Group (Upper Cretaceous – sandstones).

Aerogeophysical Project (Petrobras, 1981). The surface and subsurface structural models were matched on a common structural framework in the Geographic Information System (GIS) environment.

Potentiometric and flow data from 171 completed exploration wells in the Serra Geral Formation were evaluated. The data were provided by the Companhia de Saneamento do Paraná (Sanepar), and the Superintendência de Desenvolvimento de Recursos Hídricos e Saneamento Ambiental (Suderhsa) – Instituto das Águas do Paraná. Based on chemical analysis of 96 samples whose ionic balance difference was less than 11%, pH, total dissolved solids (TDS) and the typology of the waters were assessed.

This paper discusses the structural influence on water merging zones, as well as the compartmentalization of the two aquifer systems by comparing hydrogeological and hydrochemical maps and the integrated structural framework.

GEOLOGICAL AND HYDROGEOLOGICAL CHARACTERIZATION

The study area is located in a region with mainly volcanic rock outcrops of the Serra Geral Formation (Fig. 2), comprising the Serra Geral Aquifer System (SGAS) and constituent lithologies of the Guarani (GAS) and Caiuá Aquifer Systems (CAS). This region was affected by a number of tectonic events/structures that have shaped (fractured) the basalts, as well as the underlying Mesozoic and Paleozoic sedimentary rocks. Such structures had an important hydrogeological impact on the aforementioned aquifers, generating different behaviors.

According to Zalán et al. (1987), the Paraná Basin is a vast South American intracratonic basin fully developed on continental crust, filled with sedimentary and volcanic rocks, ranging in age back to the Silurian to the Cretaceous periods (438 Ma to 65 Ma – Fig. 3). It covers an area of about 1,700,000 km^2, extending over Brazil (1,100,000 km^2), Paraguay (100,000 km^2), Uruguay (100,000 km^2) and Argentina (400,000 km^2). Its evolutionary history is closely related to sea level eustatic changes, and associated with subsidence events occurring in intraplate domain, in response to Paleozoic orogenic stress on the west edge of the continent and the Mesozoic taphrogeny responsible for the opening of the South Atlantic Ocean (Milani, 2004).

There are two individual sub-basins in the Middle Triassic, the result of a domical uplift in the Ponta Grossa Arch region and little further south (Porto União high). The northern sub-basin accumulated the Pirambóia Formation, consisting predominantly of sandstone with medium scale and, locally, sets with large scale cross-bedding. Low-angle cross-bedded or plane-parallel stratification sandstones are also common. All these facies are characterized by the existence of sedimentary structures derived from aeolian sediment processes, in fluvial-aeolian environment, of dunes and wet interdunes. Penecontemporaneous units occur to the south, encompassed in the Santa Maria and Rosario do Sul formations. Their thicknesses vary from only a few meters in the outcrop range of the Paraná State until more than 400 meters in the subsurface, in São Paulo and Mato Grosso do Sul States (Assine et al., 2004).

In the Jurassic, the extensive fluvial-aeolian sedimentation

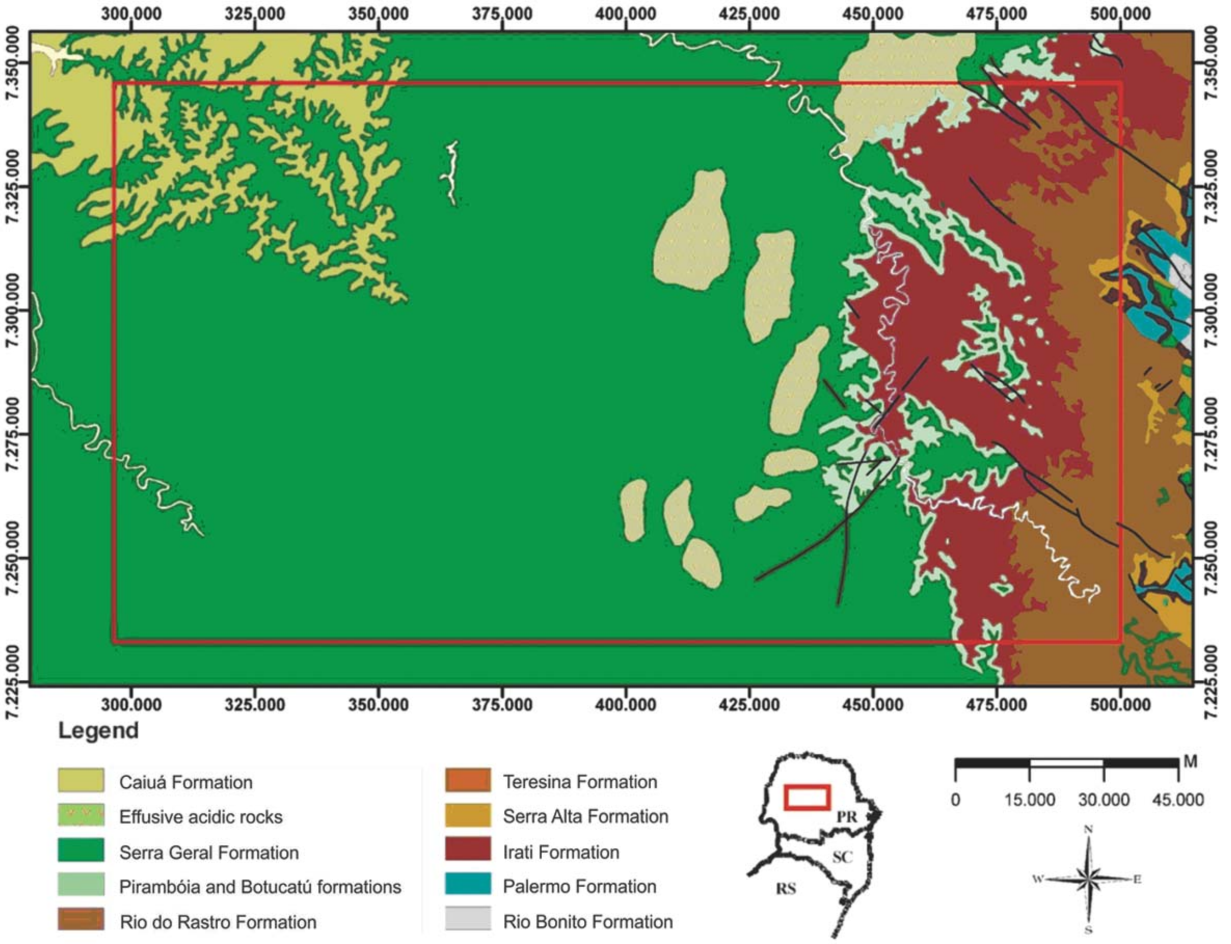

Figure 2 – Geologic map of the study area (Mineropar, 2001).

basin gradually becomes a vast desert with predominately aeolian sedimentation, dune-like, of the Botucatu Formation. This formation has sandstones with cross, planar or trough cross-bedding stratification, medium to large scale (aeolian dune fields), with rare interbedded sandstones with plane-parallel stratification (dry interdunes). Variation in thickness and facies (Assine et al., 2004) suggests that the Ponta Grossa Arch was an active element in this episode.

At the end of this cycle (Upper Jurassic to Lower Cretaceous), still under desert climate conditions, volcanic activity began, which was characterized by extensive flows of basaltic Serra Geral Formation lava, associated with intrusions in the form of diabase dikes and sills, present throughout the entire sedimentary section of the basin. The volcanic package is shown superimposed on Botucatu Formation layers, with frequent intertrapian sandstone lenses. Intercalated sandy gaps are most common in the top portions. Basaltic effusions are found at the base of the volcanic sequence, following the manifestations of intermediate nature.

After Serra Geral volcanism (Lower Cretaceous) over an erosive surface carved in basalts and other extrusive microfelsic rocks (Soares, 1991), the eolic sedimentation of the Caiuá Group began in a surface located northwest of Paraná State and west-southwest of São Paulo and Mato Grosso do Sul States.

Most of the stratigraphic and structural evolution of the Paraná Basin was controlled by basement inherited trends. This set of cratons and mobile belts contain a surprising number of zones of weakness which intersect the basement, breaking it into hundreds of mega-blocks, blocks and sub-blocks.

Zalán et al. (1987) characterized the main tectonic elements. A striking pattern of linear features in X form can be observed. These features can be divided into three groups according to their orientation (NW-SE, NE-SW and E-W), the two most important being NW-SE and NE-SW. They can be simple faults or extensive

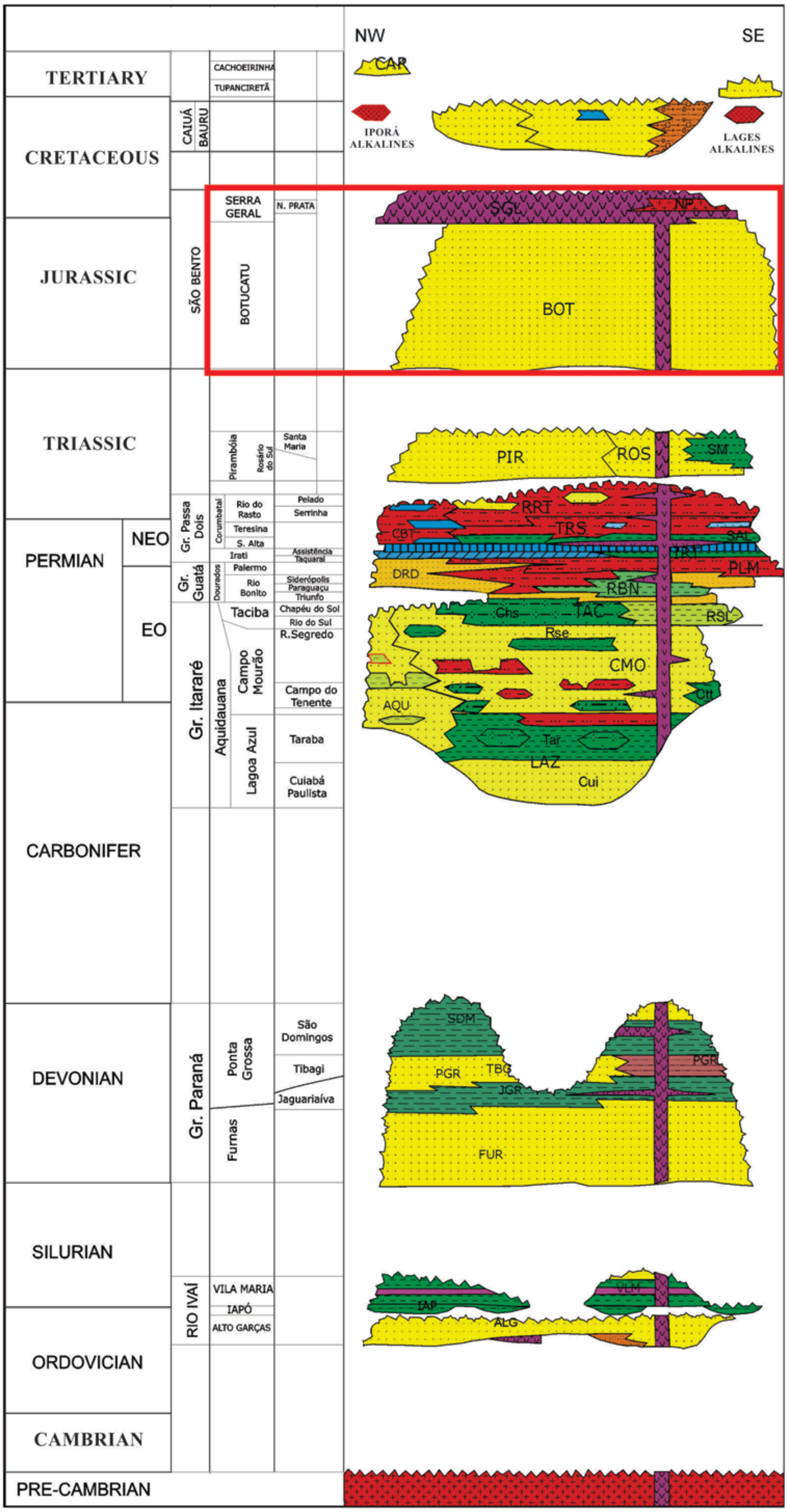

Figure 3 – Chronostratigraphic diagram of Paraná Basin (Milani, 2004).

fault zones (hundreds of kilometers long and a few tens of kilometers wide) affected by kinematics with horizontal and vertical components. Some examples include: the NW-SE trending Alonzo River Lineament, the Piquiri River Lineament and the Cândido de Abreu-Campo Mourão fault zone; and the NE-SW trending Guaxupé and Jacutinga faults, all identified in the study area. The drainages of greatest relevance are associated with these major NE and NW trending faults.

Regarding SGAS, groundwater occurrence depends on genetic factors of the basaltic package (intertrapp, amygdales, vesicles and disjunctions), as well as the presence of structures (faults, fractures and diabase dikes) that influence the flow of water through these rocks. The combination of these factors increases the water storage capacity.

This aquifer is classified by Borghetti et al. (2004) as fractured and/or fissured, formed by hard and massive crystalline rocks, where water circulates through fractures, cracks and open faults that resulted from tectonic movements. The storage capacity of SGAS is related to the amount of fractures, their openings and interconnections, which allow water infiltration and flow. Wells drilled in these rocks yield low flows, and production depends only on the degree of fracturing of rocks.

Regarding drinkability, waters in basalts show a pH between 5.5 and 6.5 and total mineralization less than 300 mg/L (Borghetti et al., 2004).

The main recharge occurs via rainfall, especially in areas with developed weathering layer, little uneven topography and considerable vegetation cover (native forest). Locally, ascending recharge from GAS may occur under favorable potentiometric and structural conditions. The typology of SGAS waters is calcic bicarbonatic, resulting from the weathering action of typical basalts. Basalts of the Serra Geral Formation cover the GAS reservoirs, reducing their exposed area to only 10%.

GAS comprises the lithostratigraphic units, formed by aeolian sandstones, of the Botucatu Formation in Brazil, Taquarembó in Argentina and Uruguay, Missiones in Paraguay; and sedimentary rocks of fluvial-lacustrine origin of Pirambóia/Rosário do Sul Formation in Brazil, Buena Vista in Argentina and Uruguay, and Missiones in Paraguay. In the State of Paraná, the GAS covers an area of approximately 131,300 km^2 (Araújo et al., 1995), about 15% of the Brazilian portion of the aquifer.

It is classified by Borghetti et al. (2004) as granular (porous or sedimentary), where water circulates through the pores formed between the grains of sand, silt and clay. An evenly distributed porosity is usually expected, allowing flow of water in both directions, depending only on the differential hydrostatic pressure, conferring an isotropic character to the system. However, recent studies showed that GAS is compartmentalized in Paraná and Rio Grande do Sul States (e.g. Machado, 2005), by major fault systems, influencing the thickness of its layers and confining strata, flow direction, and TDS content, with direct implications on water quality.

The chemism of GAS waters is highly variable, especially in confined areas, either because of facies variations, or due to the influence of fracture induced mixtures. In more confined areas of the aquifer, water has high levels of total dissolved solids (TDS$>$1,000 mg/L), high concentration of sulfates, and the presence of fluorine above the recommended limits (12 mg/L).

In the recharge area and along an adjacent strip of about 60 km, the waters have high concentrations of bicarbonate and calcium and calcium and magnesium, with dry matter contents below 200 mg/L and acidic pH. In the confined aquifer zone, in turn, the water, initially with high levels of sodium and bicarbonate, is found to contain chlorine, sodium and sulfate ions along the trough of the basin; the pH is alkaline and the TDS values range from 200 to 600 mg/L. The water temperature increases gradually from the recharge areas to the trough of the basin, according to the natural geothermal regime (1°C/35 m).

GEOPHYSICAL ANALYSIS OF THE SUBSURFACE

The geophysical and structural analysis of the basalts of the Serra Geral Formation in the study site was based on the processing of aeromagnetic data from the Rio Iguaçu Aerogeophysical Project (Petrobras, 1981), which were acquired at an average height of 500 m, with a sampling interval of 100 m, along NS production lines spaced 2,000 m, and perpendicular control lines spaced 20 km.

The magnetic data extracted from the main magnetic field (IGRF – International Geomagnetic Reference Field), were interpolated to form a regular grid with 500 m cells (1/4 of the flight lines spacing) using the minimum curvature method (Briggs, 1974). Magnetic anomaly data were micro-leveled with the Geosoft method (2003), which was considered more satisfactory than other methods, such as decorrugation (also tested), because it distinguishes geological signal from noise signals in flight lines. The micro-leveled magnetic anomaly map is shown in Figure 4.

Upward continuation procedure

As it is known, the upward continuation procedure simulates the acquisition of the magnetic field data at higher levels (more distant from the sources), removing or at least minimizing the signals from sources at shallow depth and noise. It effectively corresponds to a smoothing procedure and is regularly used to compare magnetic data taken at different altitudes.

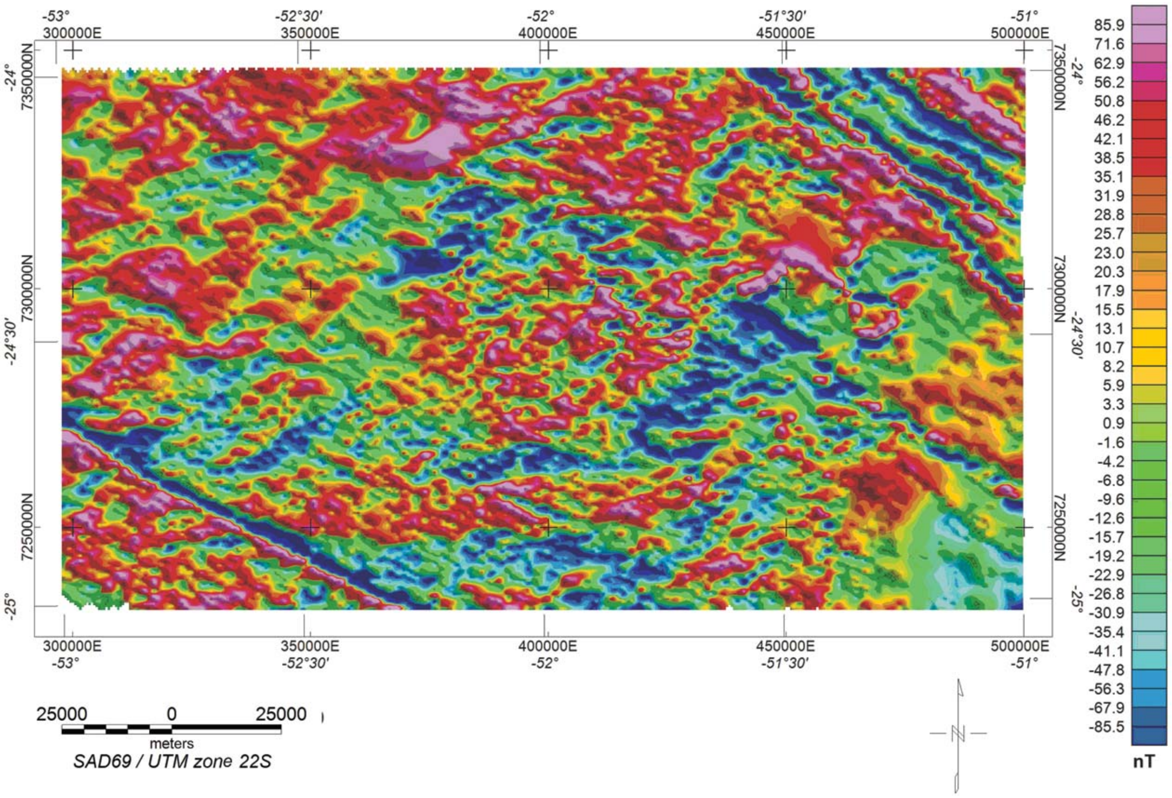

Figure 4 – Magnetic anomaly map of the study area.

The magnetic data were acquired at a height of 500 m, and were simulated for the heights of 2,000 and 5,000 m. Figure 5 shows the magnetic anomaly map upward continued to 2,000 m. This procedure caused the removal of high spatial frequency signals and noise, preserving the large wavelength anomalies, reflecting deep sources.

Total horizontal gradient

The total horizontal gradient is the resulting of the combination of the first horizontal derivatives in x and y directions of the magnetic anomaly M, given by the equation below (Cordell & Grauch, 1985):

$$GHT(x,y) = \left[\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2\right]^{1/2} \quad (1)$$

where $(\partial M/\partial x)$ and $(\partial M/\partial y)$ represent the first horizontal derivatives of the magnetic anomaly M, in x and y directions, respectively.

The map of the total horizontal gradient upward continued to 2,000 m is shown in Figure 6, which displays mainly the NW-SE direction trend.

Analytic signal amplitude

The analytic signal amplitude method is based on the horizontal and vertical derivatives of the magnetic anomaly M, whose equation is given below:

$$ASA(x,y) = \left[\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2 + \left(\frac{\partial M}{\partial z}\right)^2\right]^{1/2} \quad (2)$$

where $(\partial M/\partial x)$ and $(\partial M/\partial y)$ represent the first horizontal derivatives of the magnetic anomaly M, in x and y directions, respectively, and $(\partial M/\partial z)$ is the first vertical derivative (Nabighian, 1972).

The analytic signal amplitude is bell shaped, which peaks exactly at the top of the source, and its dimensions are directly related to the depth of the examined body, in any derivation order (Nabighian, 1974), which explains its wide use in magnetic mapping.

The analytic signal amplitude was calculated, based on magnetic data upward continued to 2,000 m and 5,000 m. Figure 7 shows the analytic signal amplitude map of the magnetic data continued to 2,000 m, where various trends, predominantly NW-SE, are observed, whose most significant anomalies are located in the NE and SW quadrants.

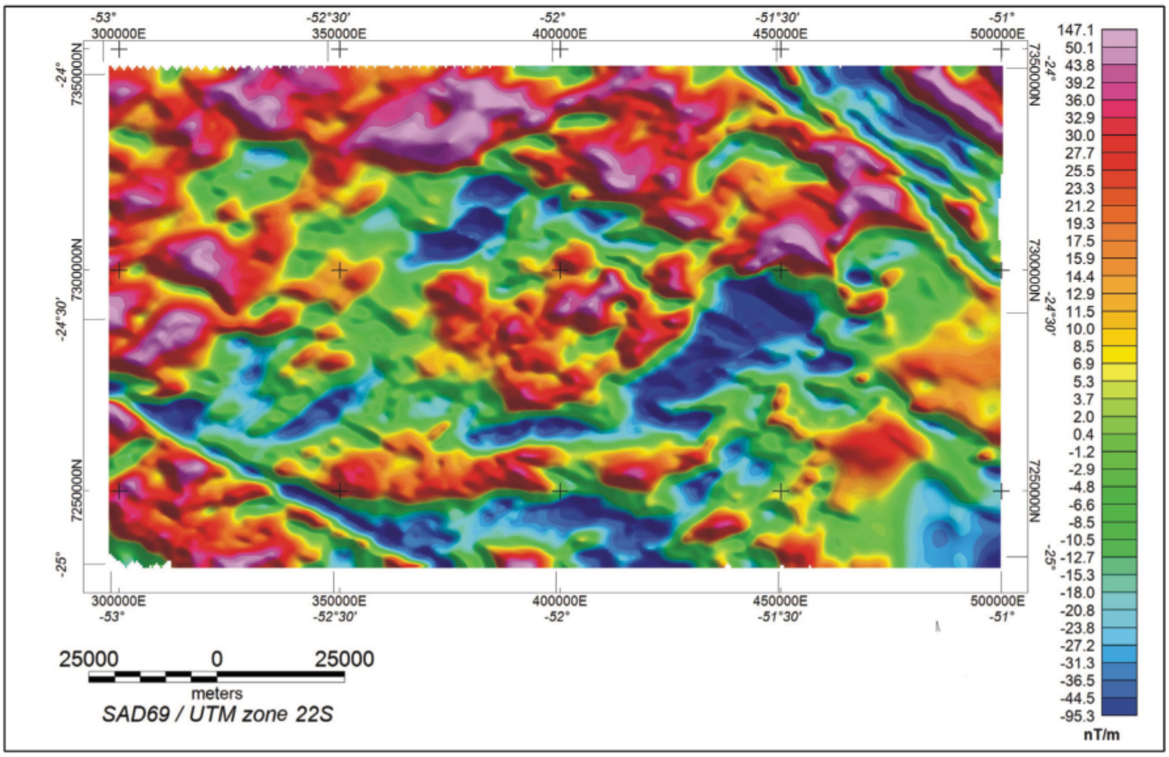

Figure 5 – Magnetic anomaly map upward continued to 2,000 m.

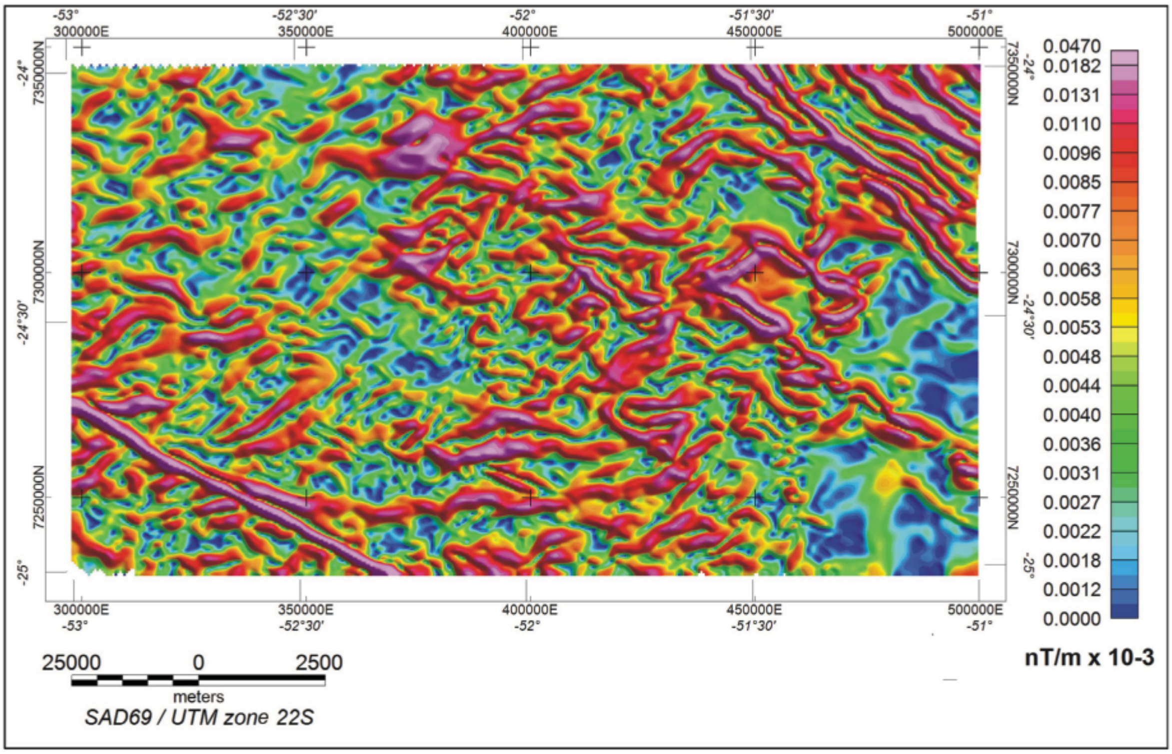

Figure 6 – Total horizontal gradient map (based on magnetic data upward continued to 2,000 m).

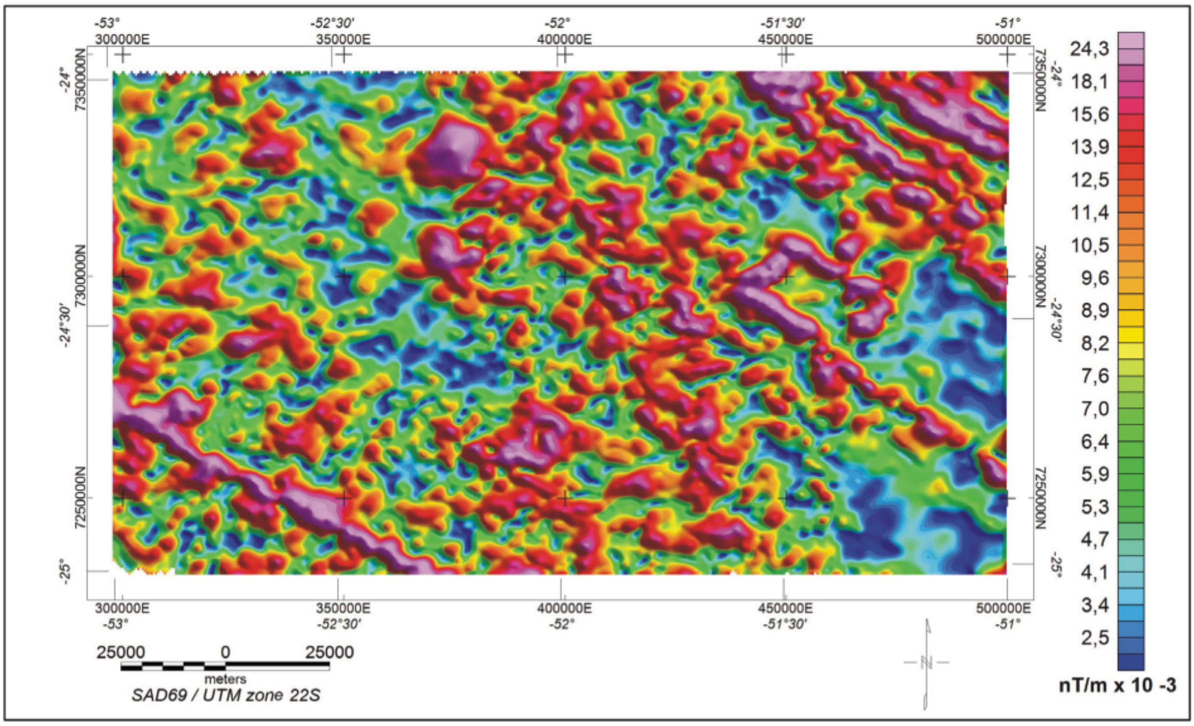

Figure 7 – Analytic signal amplitude map (based on magnetic data upward continued to 2,000 m).

Tilt angle

The tilt angle (Miller & Singh, 1994) is defined by the angle formed between the imaginary (vertical derivative) and real (total horizontal gradient) of the magnetic anomaly and can be expressed by:

$$ISA(x,y) = \frac{\dfrac{\partial M}{\partial z}}{\left[\left(\dfrac{\partial M}{\partial x}\right)^2 + \left(\dfrac{\partial M}{\partial y}\right)^2\right]^{1/2}} \qquad (3)$$

where $(\partial M/\partial x)$ and $(\partial M/\partial y)$ represent the first horizontal derivatives of the magnetic anomaly M, in x and y directions, respectively, and $(\partial M/\partial z)$ is the first vertical derivative.

The tilt angle map of the magnetic data upward continued to 2,000 m is shown in Figure 8, where the anomalies are better delineated, mainly in NW-SE direction.

STRUCTURAL ANALYSIS OF THE SURFACE

Delineation of surface structural directions, shown in Figure 9, was based on studies by Soares et al. (1982) and Zalán et al. (1987, 1990), depicting the major faults in the study area, which were confirmed by data collected on the field in conjunction with interpretation and integration of lineaments extracted from satellite images, field drainage network and the Digital Elevation Model (DEM) (Fig. 10).

The main features identified in the DEM are related to different lithologies, the drainage system and structures that affect the area. The compositional difference between these rocks can be seen in the eastern portion, where Paleozoic sedimentary rocks dominate, in the northwest portion where the Caiuá Group rocks outcrop, and the rest of the area, which is characterized by basaltic rocks of the Serra Geral Formation. A topographically low structure can also be identified in the central area, bordered by intermediate and acid effusive rocks of the Serra Geral Formation, as well.

The DEM was interpreted in two scales (1:250,000 and 1:400,000) and based on pseudo-lit images along four preferred directions (NS, NE, NW and EW), resulting in a map of lineaments of the respective directions (Fig. 11). These lineaments were statistically analyzed using the LinAnalyst software, recently developed by Freitas (2005), whose results are shown in Figure 12.

A preferred NS direction is evident, especially in the eastern portion of the area, which has been demonstrated by several authors (e.g. Portela Filho, 2003; Rostirolla et al., 2005). The NW direction is also prominent, confirmed by major faults and fault zones that intersect the area. On the other hand, the NE direction,

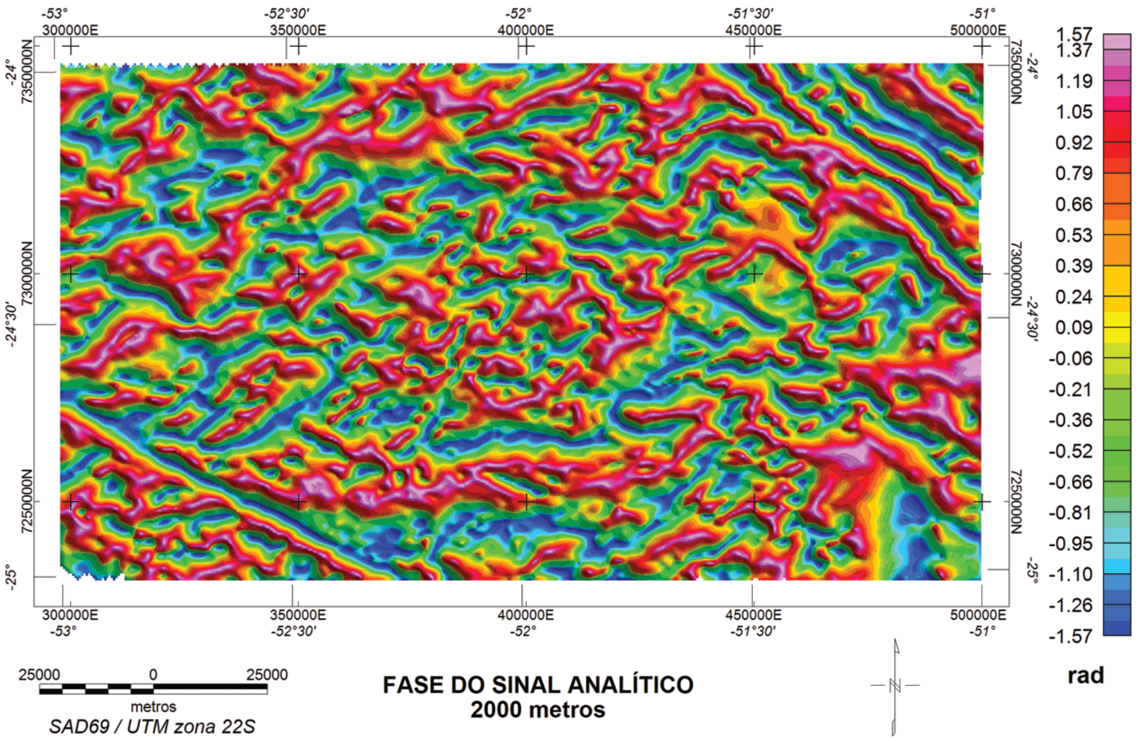

Figure 8 – Tilt angle map (based on magnetic data upward continued to 2,000 m).

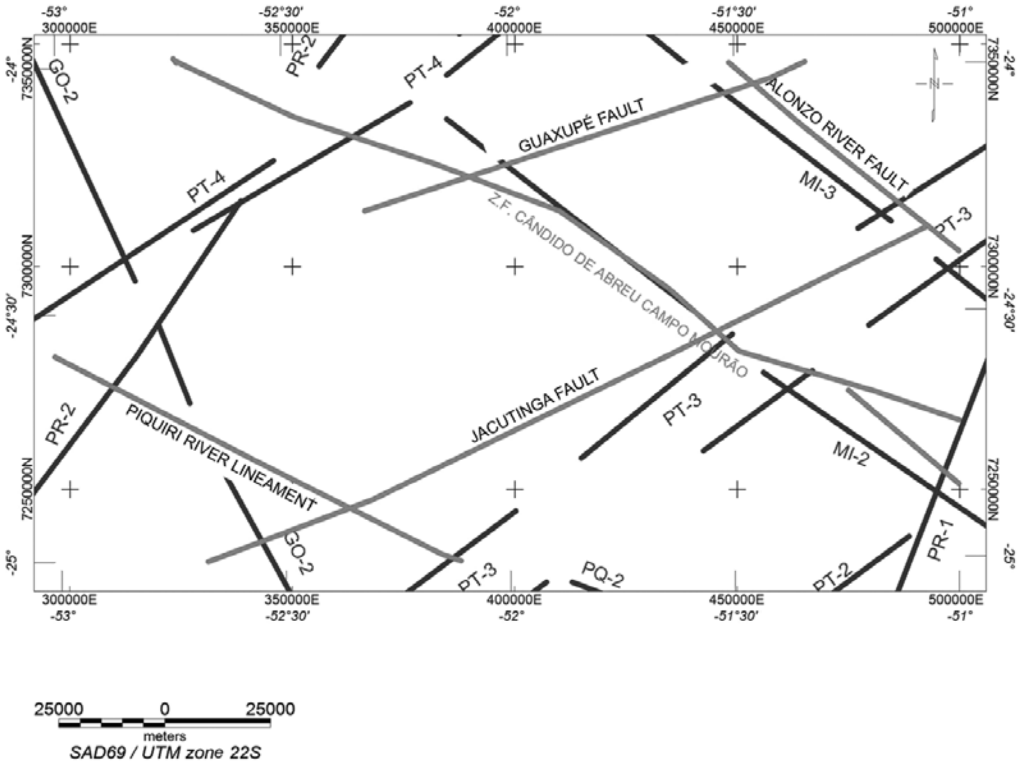

Figure 9 – Structural framework of the study area according to Soares et al. (1982) and Zalán et al. (1987).

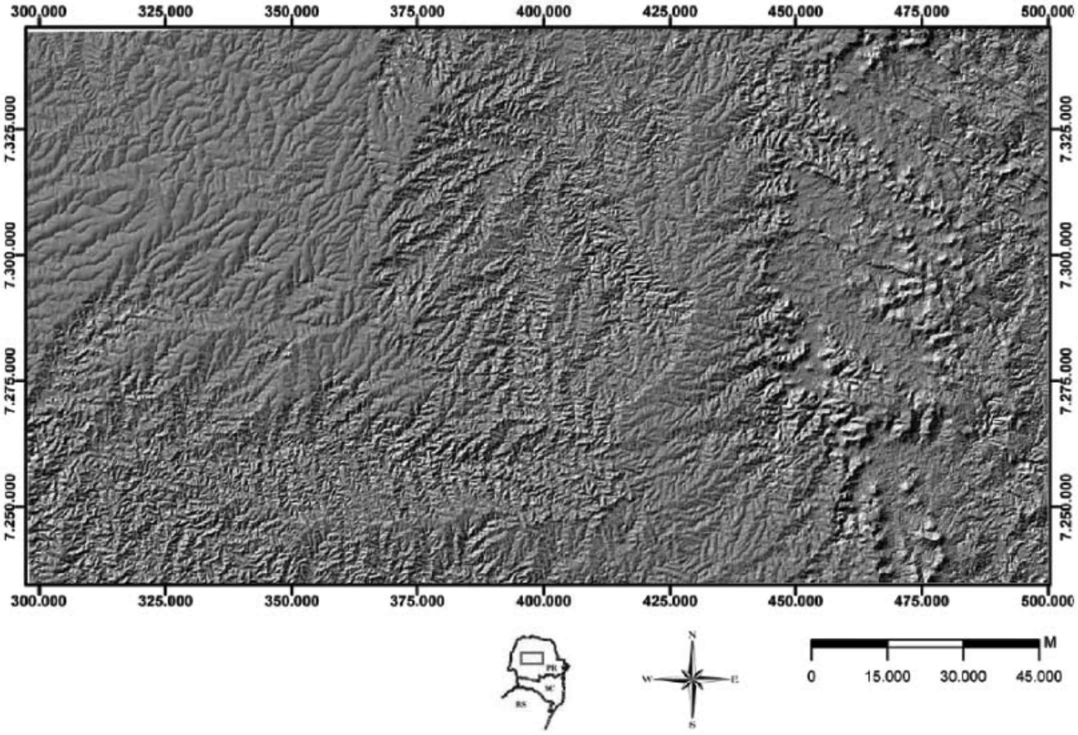

Figure 10 – Digital Elevation Model (DEM) of the study area.

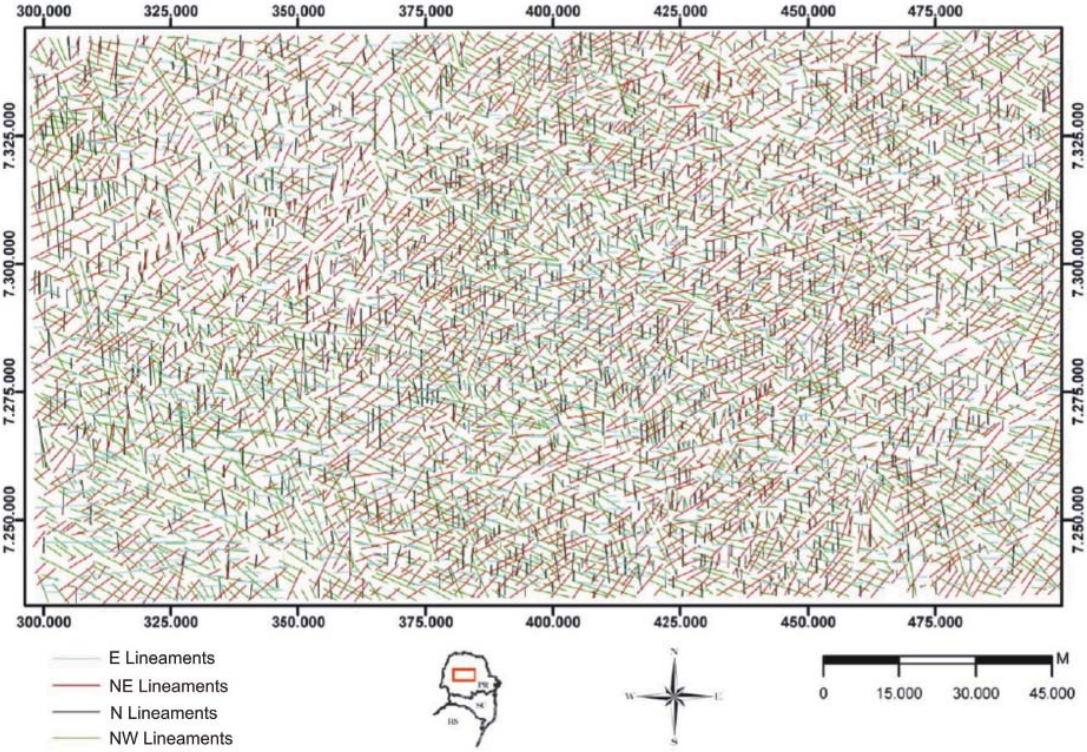

Figure 11 – Structural lineaments map interpreted using the Digital Elevation Model (DEM).

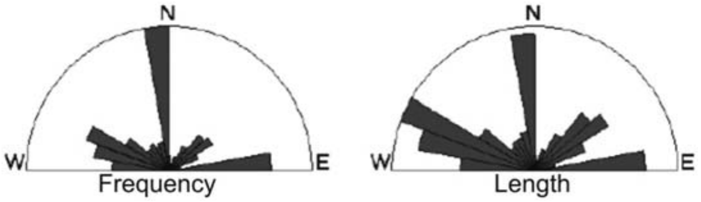

Figure 12 – Rose diagrams (frequency and length) based on Figure 11.

also associated with faults, is less intense. Finally, the EW direction, characteristic of the basin, but less studied, is noticeable in rosette-like maps.

SURFACE AND SUBSURFACE DATA INTEGRATION – STRUCTURAL-MAGNETIC FRAMEWORK

The integrated interpretation of earlier results (surface) and the results of aeromagnetic data processing (subsurface) produced the magnetic-structural framework map (Fig. 13). The faults, fault zones and lineaments were identified as defined by Soares et al. (1982) and Zalán et al. (1987). Moreover, the integrated interpretation resulted in proposed new structural lineaments, which are preferably arranged parallel to the Cândido de Abreu - Campo Mourão fault zone, but also in the EW direction near Cantú River. These structures were called Rio Cantú and Roncador lineaments (Fig. 13).

HYDROGEOLOGICAL CONTEXT

Based on the definition of the structural-magnetic framework, we aimed to evaluate the possible influences of the structures on water circulation in SGAS, as well as identify areas of connectivity with GAS and possibly with other underlying aquifers. Therefore, we considered the spatial distribution of hydrochemical variables related to the structural-magnetic framework, since it is assumed that, under favorable potentiometric conditions, GAS waters ascend through faults/fractures up to SGAS and may modify this aquifer's typical hydrochemical signature.

A total of 96 completed wells in the Serra Geral Formation were analyzed to determine flow rate, pH, total dissolved solids and potentiometry. The hydrochemical analysis were used to assess the spatial distribution of groundwater chemical typology in the region.

Potentiometry

The high correlation between the wells and the static level (potentiometric surface), suggests an unconfined aquifer behavior for SGAS, a fact already observed by Fraga (1986). Based on this finding, a map of the potentiometric surface was elaborated, which considered surface topographic data. Figure 14 shows the map of the potentiometric surface, in relation to the structural-magnetic framework, in which a SE to NW decreasing trend is observed, indicating strong structural control along this direction.

Flow

The most productive wells are located near the towns of Roncador, Pitanga, Campina da Lagoa and Altamira do Paraná, and feature high pH values. The map in Figure 15 shows that the increase in flows in the Midwestern portion of the area coincides with the NW and NE trending intersecting faults. However, high flows alone are not sufficient to characterize areas of connection between SGAS and GAS.

Total dissolved solids (TDS)

The contour map of total dissolved solids (Fig. 16) clearly shows areas of high concentration in the northeastern portion of the Cândido de Abreu – Campo Mourão fault zone and near the Rio Piquiri Lineament, suggesting structural control. Higher TDS concentrations denote waters with longer residence time in the aquifer (restricted circulation) and may suggest contribution from GAS (e.g. Bittencourt, 1978; Fraga, 1986, 1992; Rosa Filho et al., 1987; Bittencourt et al., 2003).

Hydrogen potential (pH)

The map of hydrogen potential (Fig. 17) shows that alkaline (high) values, in red, indicate trends, mainly in the northeastern portion, near the town of Jardim Alegre, and also in the southwest region, adjacent to the Rio Piquiri Lineament, another indication of structural control.

The SGAS alkaline pH can be attributed to GAS influence, since increased alkalinity results in CO_3^{2+} imbalance, which causes Ca^{2+} depletion, increasing sodium content (e.g. Bittencourt et al., 2003). Values above 7.5 were observed in the NE and SW portions of the area, associated with Cândido de Abreu – Campo Mourão fault zone and Rio Piquiri Lineament, respectively.

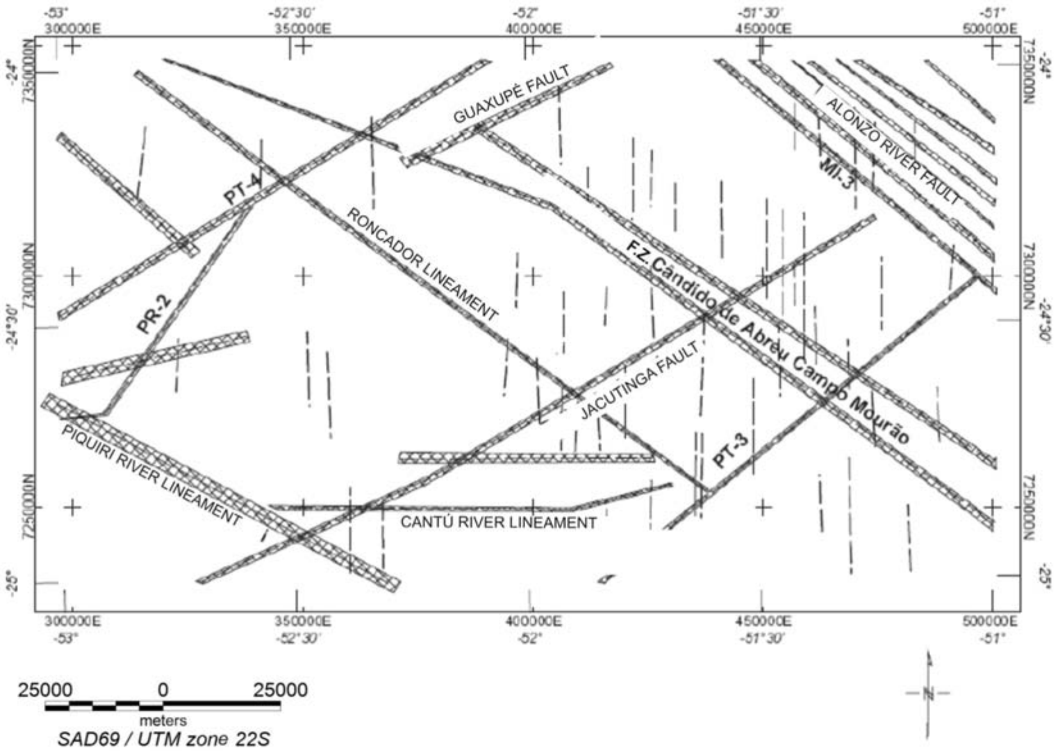

Figure 13 – Structural-magnetic framework map of the study area.

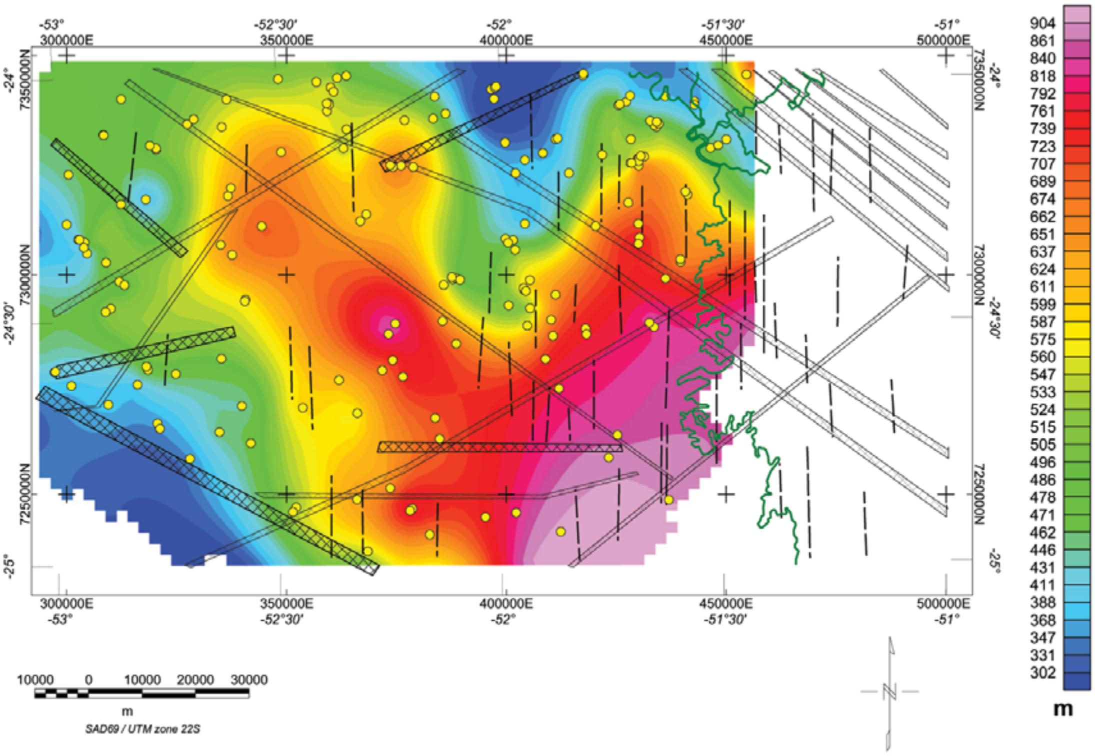

Figure 14 – Potentiometric surface map (SGAS wells in yellow, Serra Geral Formation in green and the structural-magnetic framework in black).

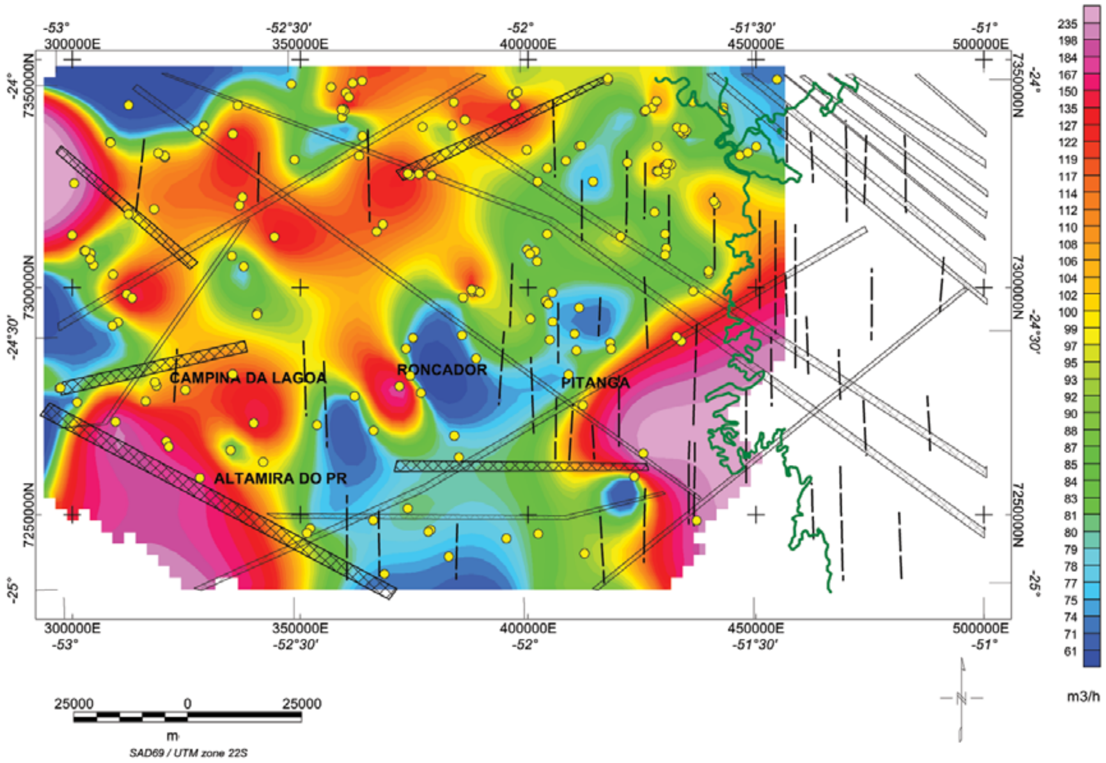

Figure 15 – Flow map (SGAS wells in yellow, Serra Geral Formation in green and the structural-magnetic framework in black).

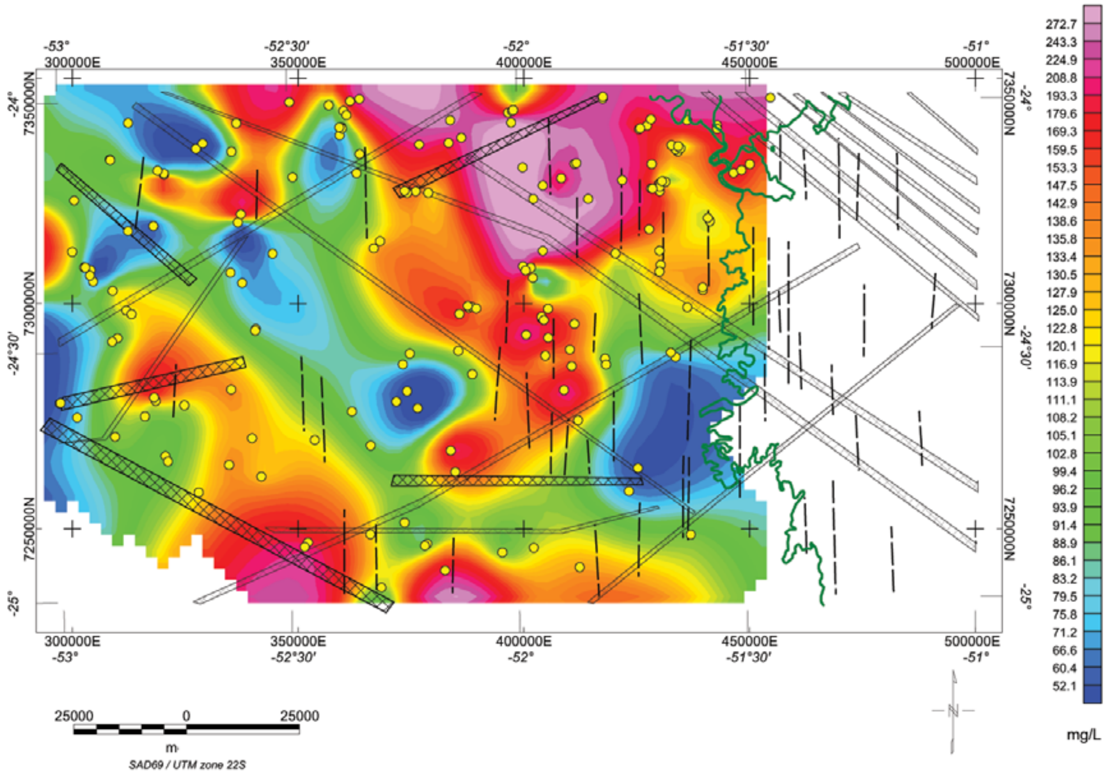

Figure 16 – Total dissolved solids (TDS) map (SGAS wells in yellow, Serra Geral Formation in green and the structural-magnetic framework in black).

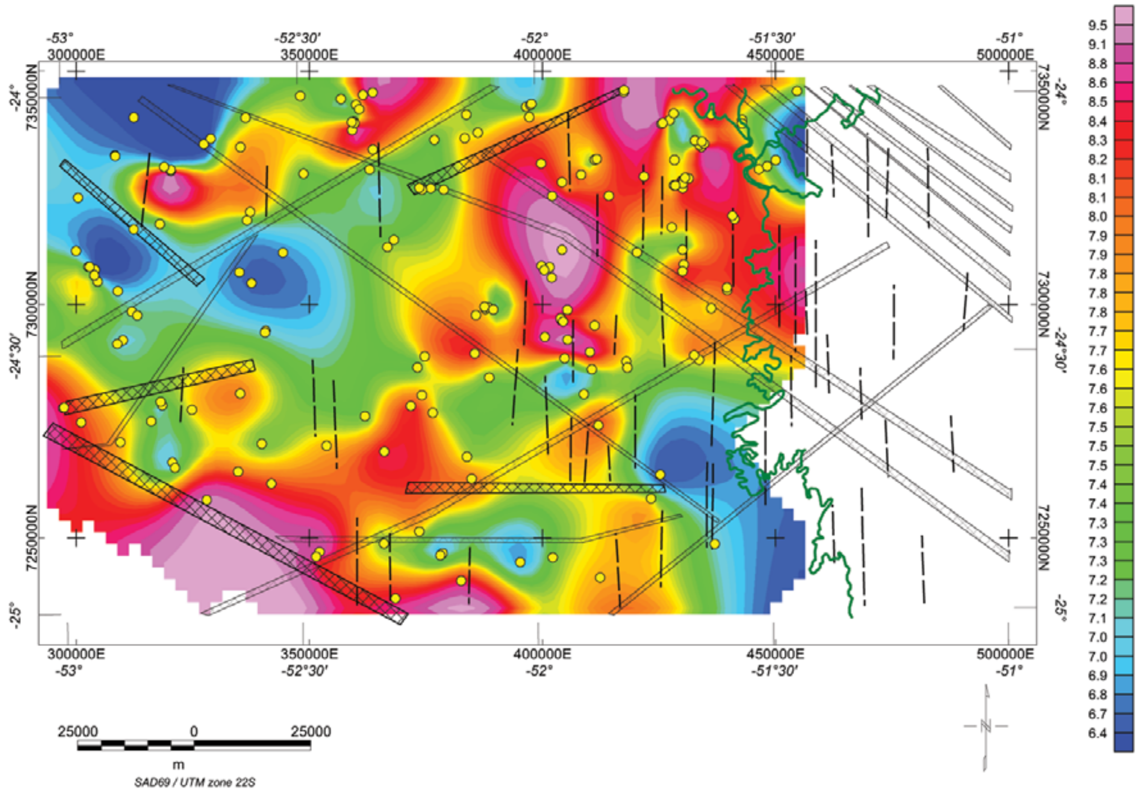

Figure 17 – Hydrogen potential (pH) map (SGAS wells in yellow, Serra Geral Formation in green and the structural-magnetic framework in black).

Typology of waters

The hydrochemical analysis that showed ionic balance difference (IBD) below 11% (96 samples) were manipulated in order to classify chemical water typology through Piper diagrams (e.g. Fraga, 1992; Bittencourt et al., 2003; Portela Filho, 2003). Through chemism, these authors distinguish typical SGAS waters from mixtures with water from other aquifers (connection with GAS) and/or those with longer residence time.

Figure 18 shows that the predominant composition of the water is calcium and bicarbonate, followed by calcium, magnesium and bicarbonate, calcium and sodium and sodium and bicarbonate.

The waters with calcium and bicarbonate are approximately 69% of the analyzed samples, characterized by an average calcium content of 15 mg/L, pH almost neutral and average total dissolved solids 111 mg/L. These waters are considered to be typical of SGAS (Bittencourt et al., 2003) or of GAS free zone (Silva, 1983).

The waters with calcium, magnesium and bicarbonate (17%) are characterized by higher average magnesium content (5.92 mg/L), pH values around 7.3 and average total dissolved solids 127.8 mg/L. For Bittencourt et al. (2003), higher magnesium levels may well relate to SGAS, while for Silva (1983) they characterize hydraulic connectivity zones.

In waters with calcium, sodium and bicarbonate (10%), pH is around 7.6 and the total dissolved solids average around 145 mg/L. The average sodium value (13.2 mg/L) suggests a mixture of water from different aquifers or longer residence time (e.g. Bittencourt et al., 2003).

The waters with sodium and bicarbonate, typical of totally confined GAS zones (e.g. Silva, 1983; Hirata & Sracek, 2002), represent 6% of the total samples and are associated with high sodium levels (59 mg/L), average pH of 9.1, and average total dissolved solids of 245 mg/L.

The map in Figure 19 shows the spatial distribution of the chemical typology of SGAS waters in relation with pH and TDS values.

Finally, Figure 20 summarizes data interpretation in terms of possible areas of hydraulic connectivity of SGAS and GAS (wells in red, area in pink). The wells in blue are characteristic of typical SGAS waters. It is presumed that these areas are marked by rhombohedral NW-SE and NE-SW structures, in which the residence time of water is higher.

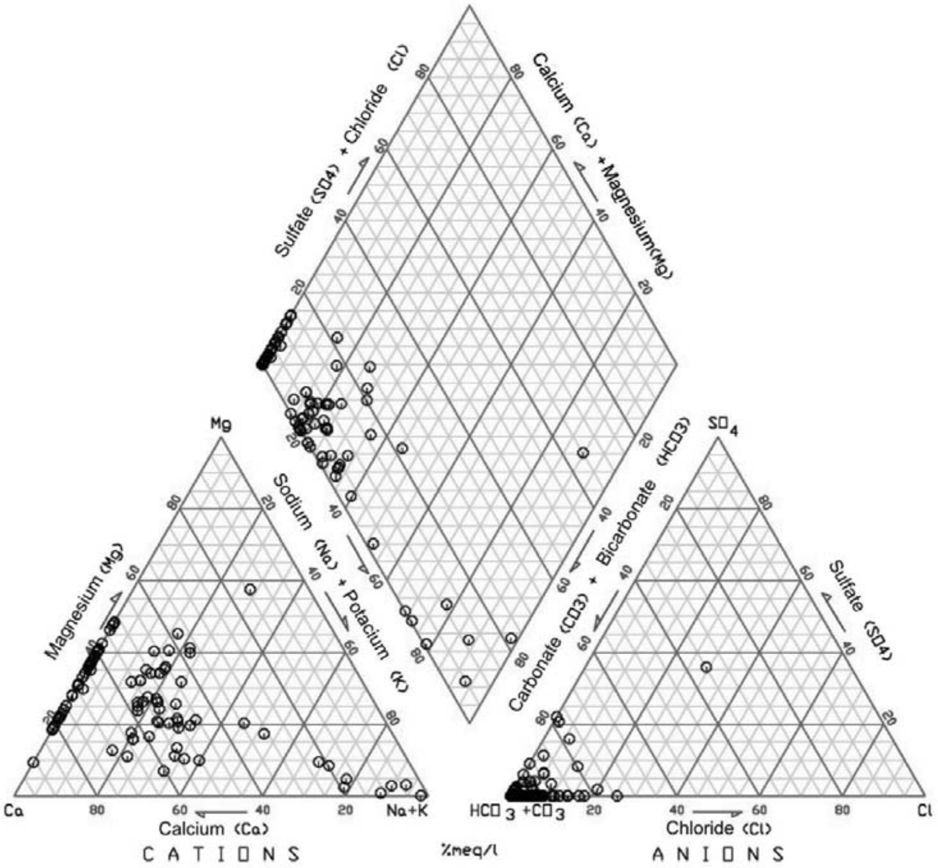

Figure 18 – Piper diagram of the study area.

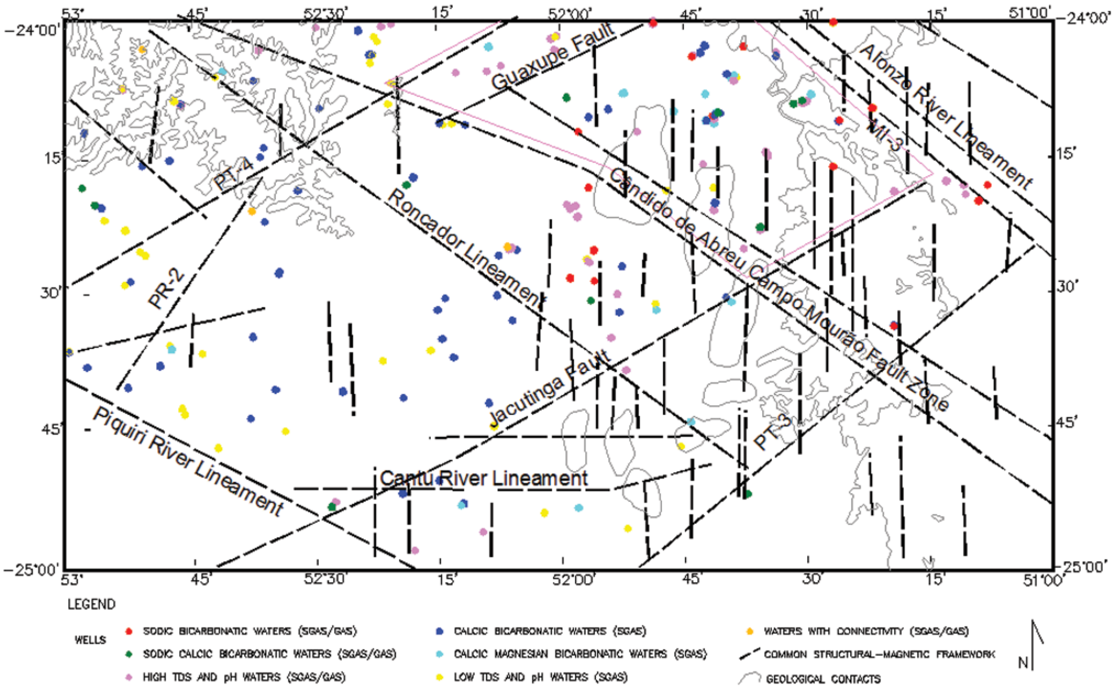

Figure 19 – Hydrochemical types of the SGAS map.

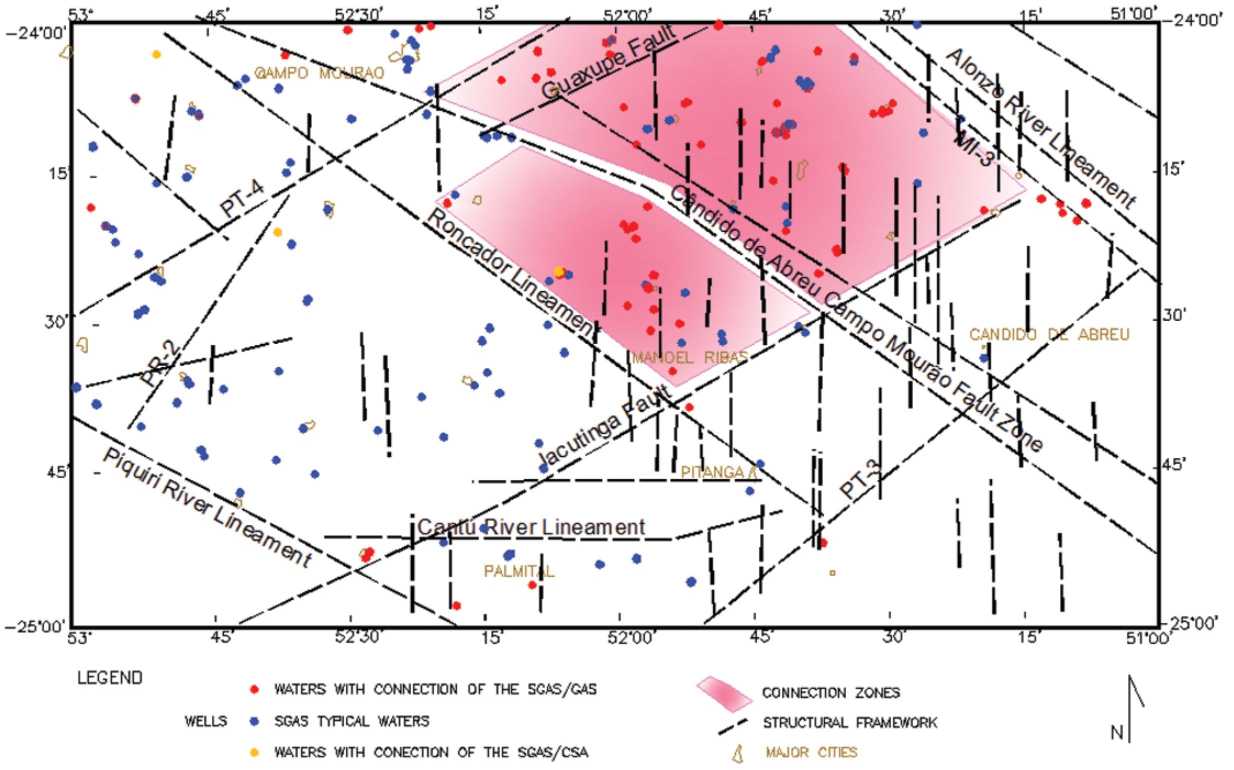

Figure 20 – Connectivity zones of SGAS and GAS (pink) interpretation map.

DISCUSSION

Recent studies on the structures and their influence on the flow and storage of water in Serra Geral and Guarani aquifer systems in Paraná State, by Portela Filho et al. (2002), Strugale (2002), Strugale et al. (2002), Portela Filho (2003), Ferreira (2005), Ferreira et al. (2005), Portela Filho et al. (2005), Mocellin & Ferreira (2009), Bongiolo et al. (2011), among others, have made it possible to define the Ponta Grossa Arch central region, as described by Ferreira (1982a,b), characterized by intense faulting and intrusions of diabase dikes, as the main tectonic feature determinant of the flow and chemism of waters in both systems, which demonstrates a particular hydrogeological behavior for the State of Paraná.

As a result of this behavior, we note that GAS is locally discontinuous and often in contact with the side of the Rio do Rastro and Serra Geral formations. It is also noteworthy that the hydraulic pressure of the upper (Serra Geral Formation – SGAS) and lower packages (Botucatu/Pirambóia Formations – GAS) almost always causes upflow, and there are few resurgences (natural springs), according to the model proposed by Fernandes et al. (2007).

As already mentioned, for the State of Paraná, significant differences in hydraulic and hydrochemical characteristics of wells relatively close to SGAS and GAS can be interpreted as resulting from specific structural conditions, which compartmentalize the aquifer systems and regulate groundwater flow.

In order to better understand the areas of connectivity of Serra Geral and Guarani aquifer systems, structural-magnetic framework and chemical data derived from 96 completed wells in Serra Geral Formation were integrated in the Geographic Information System (GIS). In this paper, interpretation of hydrogeological and hydrochemical variables, related spatially to the structural-magnetic framework, suggests a tectonic dominance of these variables, especially in the northeastern portion of the area.

The Piper diagram showed that the preferred composition of the water is calcium and bicarbonate (69%), followed by calcium, magnesium and bicarbonate (17%), calcium, sodium and bicarbonate (10%) and sodium and bicarbonate (6%). According to Fraga (1992) and Bittencourt (2003) classifications, waters with composition other than calcium and bicarbonate (typical of SGAS) may be related to areas of greater residence time or hydraulic connectivity zones, which are located in the northeast portion of the area, north of the Roncador Lineament, near Cândido de Abreu – Campo Mourão fault zone.

CONCLUSIONS

The generation of the subsurface structural framework was based on interpretation of aeromagnetic data from various methods of enhancing anomalies, which, together with surface data, allowed refining the structure of the area, including the proposal of new lineaments along NW and EW directions (Roncador and Cantú, respectively).

The NS trending structures observed were not detected in the aeromagnetic maps because of the microleveling processes and their parallelism to flight lines. However, the Digital Elevation Model (DEM) outlined some NS trends, the most prominent being along the Ivaí River.

Regarding groundwater behavior, this study sought to demonstrate that, despite its regional character and based on available data, hydrogeological and hydrochemical parameters of the Serra Geral Aquifer System are dominated by the proposed structural frame.

Interpretation of hydrochemical signatures, potentiometric surface maps, flow rates, TDS, and pH, allowed discriminating regions of predominance of typical SGAS waters from those of different composition. The latter are confined to restricted rhombohedral compartments trending primarily NE and NW, located in the northeastern portion of the study area and considered to have connection with GAS.

From the results of the different analysis, it was possible to conclude that the faults located in the northeastern portion of the study area act as flow barriers and restrict groundwater in structural compartments with different characteristics within the SGAS, indicating higher water residence time.

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