The geology of the Capiru Group, Curitiba Terrane, Southern Ribeira Belt (Brazil)

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ABSTRACT
The Capiru Group is a Neoproterozoic metasedimentary unit that crops out in the Curitiba terrane, Southern Ribeira Belt, Brazil. A detailed geological mapping of this unit was performed during 2016 to 2020. Original interpretations and the new geological map were compiled and integrated with the past field data of the state (MINEROPAR) and national (CPRM) geological surveys, and to unpublished and recent published studies. This compilation represents the most updated synthesis of the Capiru Group, and provides the basis for recognition and individualization of lithostratigraphic units. The lithostratigraphic units reflect depositional/tectonic events, which involved: a) passive continental margin deposition on the Curitiba microplate, b) compressional episodes during the Brasiliano – Pan African Orogeny (Late Neoproterozoic), c) extensional processes that followed the collision stage (Cambrian), and finally, the d) extensional tectonics related to the Gondwana break-up during the Lower Cretaceous, that culminated to the Proto-Atlantic Ocean opening.

KEYWORDS
Neoproterozoic; Curitiba microplate; Southern Ribeira Belt; Brasiliano – Pan African Orogeny; South Atlantic opening; Gencezoic Rift of Southern Brazil

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1. Introduction
The Capiru Group is a Neoproterozoic metasedimentary unit located in eastern Paraná State, Brazil, within the Precambrian shield – a rugged E-W plateau shaped on igneous and metamorphic rocks (Figure 1(A)). The Capiru Group is affected by collisional and extensional tectonics, related to the Gondwana assembly and its subsequent breakup (Brito Neves et al., 2014; Faleiros et al., 2016; Florisbal et al., 2014; Fuck et al., 2008; Heilbron et al., 2004; Owen-Smith et al., 2017; Rossetti et al., 2018). The 4 km-thick stack is bounded to the north by the Lancinha Shear Zone and to the south by the Atuba Complex basement rocks (Figure 1(B)). To the east, the Serra do Mar Ridge defines the geomorphologic boundary between the Precambrian plateau and the Atlantic Ocean coast areas (Figure 2), whereas to the west, the Capiru Group is considered as a portion of the Precambrian basement that underlies the Paraná basin (Ordovician-Cretaceous).

The research interest for the Capiru Group units dates from the 1960s, with a relative increase during the 1990s, based on interest in limestone units. During the subsequent years, the exploitation of carbonate rocks, and the groundwater hosted in karstic and fractured aquifers, resulted in a series of mapping surveys and academic research in the region. Since 1978, the (unfortunately) extinct Geologic Survey of Paraná (MINEROPAR) completed a series of projects, some of which included geological maps with variable scales and purposes. Those maps were extensively studied in order to integrate the data in this new map. During the 1990s, Fiori (1992) published a structural map of the region, which is considered the first synthesis of modern knowledge about the tectonics of the Capiru Group. Due to constant advances in geochronological techniques, some of those units were revisited and tectonic models were re-evaluated; as a result, major edits were made regarding prior geologic cartography in this contribution.

The map presented here (Main Map) is at 1:150,000 scale and was based on our mapping survey (2016–2020, 1:5,000–1:25,000) and the 1:250,000 map by Fiori (1985). It also takes into account and includes the results of Geological Survey of Brazil mapping projects, which were carried out over the last 25 years in Paraná State, as well as other maps and information published by other authors in a series of academic works developed in the Graduate Program of Geology at the Federal University of Paraná and the University of São Paulo (in Portuguese: Bahniuk, 2007; Filpi, 2021; Fiori, 1991; Guimarães, 2002; Juschaks, 2006;
Leandro, 2016; Siga Jr, 1995; Silva, 2010; Yamato, 1999). One of the major sources of geological data used in this work, if not the main, was the detailed 1:10,000 dataset provided by the mapping courses held in the Geology Department, at the Federal University of Paraná, especially those carried out since 2014, which have digital sources of information.

The aims of our mapping work and integration were to define a stratigraphic nomenclature, and to resolve some of the problems related to regional correlation.

The ‘lithologic assemblages’ of Fiori (1991) were elevated to formation status and three newly defined units – the Santana, Morro Azul, and Bocaina formations were included within the Capiru Group. The ‘Setuva Formation’ definition was replaced by the term ‘Setuva Complex’, which is used now to refer only to the granitic rocks that constitute the basement beneath the metasedimentary cover. In certain cases, the boundaries between previously recognized formations have been redefined. This explanatory text supplements the new

**Figure 1.** (A) Aerial image of Curitiba and surrounding regions. Red polygon depicts the location of the mapped area and (b) geological context of the Capiru Group within the Curitiba Terrane, after Fiori (1985). MASZ: Morro Agudo Shear Zone, LSZ: Lancelinha Shear Zone.
map (Main Map) and provides background information to assist in its interpretation. This text also describes the historical antecedents of the map, and the sources from which the map was compiled, with the aim of discussing the general topics related to it.

1.1. Sources of information

Source data for previous geologic maps comprising the Capiru Group are plentiful, so we have chosen to present a narrative account. This section describes the circumstances under which the maps were prepared and comments on their more interesting features, rather than providing a list of details, which readers can find in the published sources.

1.1.1. Maps before 1980

Concerning the pioneer works regarding the geologic mapping of the Paraná state, we acknowledge the works carried out by Oliveira (1918), Oliveira (1927), Oliveira and Leonardos (1943), and the classic published article of Maack (1947), written as a text to accompany sketches made to the revision of the Geological Map of South America. Fortunately, these early works are currently available online in the files of the Brazilian Archives of Biology and Technology. Historical details and footage of one interesting treatise about the first geological commissions in south-west Brazil, are listed in the Pinto and de Assis Janasi (2015) work, published in Terraes Ditatica, a Journal of the Campinas State University.

The following years were very fruitful for the geology of Paraná State. During this time, the works of Bigarella (1948) and the classic series of Preliminary Studies of the Açunungui Group, by Bigarella and Salamuni (1956, 1958) were documented. Our recent research found copies of these works in the Science and Technology Library, at the Federal University of Paraná. The 1958 can be easily found because it is indexed online in the Boletim Paulista de Geografia. The very first systematic geologic survey of Paraná was carried out by the Paraná Geologic Commission, which was established in 1964.

In 1974, the Federal Department of Mineral Production (extinct DNPM, currently ANM – Bureau of Mines of Brazil), within the scope of the 1:1,000,000 Geologic Map of Brazil, presented new maps covering the Paraná territory. In 1977, the East Project (a partnership between the DNPM and the Geologic Survey of Brazil – CPRM), developed new geological maps for the eastern portion of the state, in 1:100,000 scale.

Some of the maps of the Geologic Survey of Paraná were extensively studied in order to integrate the data in this new map. The technical reports related to these projects are now available at the Water and Land Institute of Paraná (IAT) website, many of them in digital forms.

1.1.2. 1980s maps

In the 1980s, many projects in partnership with the Federal University of Paraná led to a series of maps and academic works including the Southern Ribeira Belt units. For this study, we consulted projects that describe the ‘Capiru Formation’ as their primary focus; those projects are highlighted herein. The Phosphorite project (Projeto Fosforita) was a series of internal reports that contain a systematic outcrop study and geologic maps of research targets, from which many outcrops in the southwestern portion of the Capiru Group were revisited for this study (Cava & Falcade, 1986). In addition, two geologic maps made under the project entitled Geologic integrated studies of the Paraná Precambrian units (Estudos
were used as a base for the new survey presented herein. Although this project led to compilation of a series of maps and reports, the two of particular importance for this study were the Geologic map from the integrated studies of the Paraná Precambrian shield (Fiori, 1985) and the Geological Map of Paraná State, in 1:650,000 scale (Mineropar, 1989).

1.1.3. 1990s works
Several academic works were completed during the 1990s; these included numerous descriptions of the ‘Capiru Formation’ in addition to interpretations regarding the history of the Curitiba Terrane (Siga Jr, 1995). These works, which are extensively cited, are those of Fiori (1991), Fiori (1992), Fiori and Gaspar (1993), Siga Jr (1995), Yamato (1999), and the papers of Basei et al. (1992, 2008), included within the project: Geochronological Map of the Precambrian terrains of Paraná and Santa Catarina States; most of which were published in peer-reviewed journals – which has allowed for further dissemination of more recent regional tectonic models.

1.1.4. Integration of previous works and digital datasets
Our work started with a review of the digital integration made by the Geologic Survey of Paraná in 2001. Their compilation includes several of their projects, of variable scales, and is presented as the Curitiba Geological Chart (1:250,000). In addition to this database, the geologic units of the Precambrian shield of Paraná have been surveyed every year since 1975, during the annual mapping courses taught by the Geology Department, Federal University of Paraná. This has resulted in detailed 1:10,000 scale geologic maps, which include the following geologic features: mapped rock types, structural and tectonic aspects, and environmental features. The University’s survey mosaic is systematic, constantly updated, and the portions of the mosaic that cover the Capiru Group were integrated as a regional map for this project.

In addition to that, the increasing demand for water production around the urban areas of the Paraná Precambrian shield (Figure 2) led to the integration of the carbonate units of the Capiru Karstic Aquifer into the public supply system of the region. This demand for groundwater exploitation resulted in smaller, new surveys conducted by the Water Supply Company of Paraná (SANEPAR) in partnerships with the IAT and the Federal University of Paraná. Some academic works regarding the hydrogeological aspects have been conducted in the Capiru Group water-producer units (Filpi, 2021; Rigoti, in prep), with projects in development at the Laboratory of Hydrogeological Research (Laboratório de Pesquisas Hidrogeológicas – LPH, Federal University of Paraná).

2. Methods
Standard geologic field mapping practices were applied in the available exposures of the Capiru Group, aiming to identify major structural or stratigraphic discontinuities. The Main Map has been compiled using both published and unpublished data (See Section 1.1). It is noteworthy that the geological features of the Ribeira Orogenic System are hindered by generally poor outcrop exposure and intense weathering processes that have produced thick regolith and soils covering the underlying bedrock.

Further evaluation of target map areas and the location of some geological contacts were taken from the airborne magnetometric and gammaspectrometric survey by the Geologic Survey of Brazil (CPRM, 2011); flight lines were about 500 m self-spaced in N-S direction. The final geophysical grids were 250 x 250 m cell-sized, which were interpolated with the bi-directional algorithm and using the N135 preferential azimuth (Geosoft, 2001).

Due to the remarkable magnetic signature of the Ponta Grossa Arch (PGA) dyke swarm, the precise location of major NE-SW oriented basement structures can be hidden by several NW-SE narrow magnetic anomalies. Therefore, the magnetic anomaly was filtered with directional cosine (Geosoft, 2001), in order to mitigate the NW-SE tendency and to enhance magnetic patterns from the basement units. This procedure consists of mitigating N135-oriented magnetic anomalies which represent the PGA anomalous axis (Alves, 2006; Shukowsky et al., 2006).

3. Geology

3.1. Lithostratigraphic units
The Main Map provides an overview of the geology of the Capiru Group, where the rocks crop out in a folded belt about 24,000 km². These rocks record some of the most important global geological events that occurred during the Neoproterozoic Era (1000 – 541 Ma). They are as follows: the evolution of a passive margin after the Rodinia continent breakup (Neoproterozoic), the closure of the Brasiliano oceans (Neoproterozoic – Cambrian) during the Brasiliano – Pan African orogeny (Brito Neves et al., 2014), and the events that culminated in the Gondwana assembly (Brito Neves et al., 2014; Faleiros et al., 2016; Fuck et al., 2008; Heilbron et al., 2004). Gondwana assembly was followed by subduction that led to infilling of the Paraná intracratonic basin (Ordovician – Cretaceous), the breakup of Gondwana, and the opening of South Atlantic Ocean (Jurassic – Cretaceous), (Florisbal et al., 2014; Owen-Smith et al., 2017; Rossetti et al., 2018).

The map presented in this study includes the following:
(1) The Capiru Group basement, composed of medium-grade metamorphic rocks of the Setuva Complex, including banded gneisses and deformed granitoids, which crop out as the core of the Setuva Antiform Structure (See Section 3.2).

(2) The Capiru Group, which includes from bottom to top six different formations: Santana, Juruqui, Rio Branco, Morro Azul, Morro Grande and Bocaina, following the stratigraphic proposal of Santos et al. (2021). Those units represent distinct stages of a passive continental margin to syn-orogenic evolution, deposited on the continental shelf of the Curitiba microplate. Nevertheless, the depositional age of the Capiru Group has not been well constrained. Detrital zircon dating (SHRIMP U–Pb) provided a unimodal distribution of ∼2.2 Ga aged grains from quartzites of the Rio Branco Formation (Basei et al., 2008), whereas LA-ICP-MS U–Pb of the Morro Grande Formation has yielded only rare 1.4–1.0 Ga ages in addition to the same ∼2.2 Ga Paleoproterozoic ages. However, based on other constraints – such as elevated levels of iron, stromatolite occurrences, and Neoproterozoic aged grains in the overlying Turvo-Cajati Formation – the succession may be as young as Neoproterozoic (Cury et al., 2017; Siga Jr et al., 2012).

(3) The Serra Geral dykes (Lower Cretaceous, ∼132 Ma, Renne et al., 1996) are correlative to the basalts of the Paraná-Etendeka Igneous Province, which is interpreted to represent a large volume of subaerial lavas, dike swarms, and other intrusive igneous rocks that mainly record tholeiitic affinities. These volcanic rocks are distributed over central South America (Brazil, Argentina, Uruguay, and Paraguay) and a small part of southwestern Africa (Namibia and Angola). In Brazil, they are stratigraphically referred to as Serra Geral Formation. The Paraná-Etendeka Igneous Province represents a major magmatic event of the Lower Cretaceous and precedes the dismembering of Southern Gondwana and opening of the South Atlantic Ocean (Rossetti et al., 2018).

3.2. Structure

The deformation patterns in the area have been a controversial topic since the earliest works in the region (Fiori, 1992). In the last 30 years, structural models were proposed to explain the distribution of Capiru Group units, and new concepts and ideas were included into the previous ones (Faleiros et al., 2016; Leandro, 2016; Santos et al., 2018). Our model takes into account different levels of contributions from: (i) the Fiori (1992) model, which recognized the Setuva and Morro Grande thrusts as the main D1 phase structures; (ii) the Pinheiro Jr et al. (1998) integration and mapping (Mineral Provinces – Açungui and Setuva region) that represented some of the interference patterns between the collisional thrusts and the late-stage of transpressive tectonics; (iii) the Yamato (1999) mapping of the Bocaiúva do Sul region, which interpreted the protoliths to metamorphic products in distinct structural contexts that provided a description of the main metamorphic surfaces in the region; (iv) lastly, the Faleiros et al. (2016) tectonic model (carried out in the adjacent Turvo-Cajati Complex rocks), which presented a dynamic tectonic model of the region based on metamorphic data, ⁴⁰Ar/³⁹Ar dating, and chemical dating of monazite, in addition to a detailed description of the deformation phases. Two main ductile deformation phases were recognized through our field observations: the D1 phase is supported by sub-parallel slaty cleavage (S1), poorly defined in the northern flank of the Setuva Antiform Structure, due to overprinting by S2 surface (Faleiros et al., 2016).
et al., 2016). Tight to isoclinal folds are rare and restricted to the vicinity of F1 thrusts. Also, zones of high strain and locally higher metamorphic grade or mylonitization are restricted along the D1 thrusts-planes (Santos et al., 2018). Fiori (1992) recognized the folded-thrust F1 Setuva and Morro Grande faults along the Setuva Antiform Structure, and identified the Setuva thrust as the main detachment horizon of the Capiru Group in relation to the Setuva core domain.

The D2 phase is represented by a series of oblique-slip faults, where the Lancinha Shear Zone is the main fault of the system, its secondary structures (as the N70E system represented on the Main Map), in addition to a series of closed asymmetric mesofolds.

The Setuva Antiform Structure (See Main Map) is the most striking feature in the mapped region (Figure 3), which is described by early workers as a large E-W trending anticlinorium stack that exposes a granitic basement core (Siga Jr et al., 2007) and the Capiru Group along its rims (Campanha & Sadowski, 1999; Fiori, 1992; Fiori et al., 2003; Siga Jr et al., 2007). The axial plane of the structure trends ~N60–70E, dipping 20° to SW (Fiori, 1992). The main metamorphic foliation in the region is generally a crenulation cleavage (S2), which is better developed in the northern flank of the structure.

After theescape-tectonics stage during Neoproterozoic – Cambrian, the region went through long phases of extensional tectonics, with NW-SE faulting that led to the emplacement of the dolerite dyke-related to the Ponta Grossa Arch (the dyke swarm source). The Ponta Grossa Arch is related to the rifting process that led to the Atlantic Ocean opening, which was responsible for reactivating a series of basement structures, restructurings older basins and creating new ones (Almeida et al., 2013; Raposo & Ernesto, 1991; Ruiz et al., 2009; Strugale et al., 2007). This rifting has been linked to the activity of a mantle plume (Tristão da Cunha) that was under the South American platform during Mesozoic time (Castro-Valente et al., 2007; Morgan, 1981; O’Connor & Duncan, 1990).

The extensional events related to the Continental Rift of Southern Brazil (Riccomini, 1989; Riccomini et al., 2004; Riccomini & Assumpção, 1999) during the Cenozoic, led to the opening of a series of small and N-S aligned basins, including the Curitiba basin (Figure 1(B)).

Table 1 summarizes the geologic events responsible for the main structures represented on the Main Map, and their available ages.

### 3.3. Aerogeophysical features

Magnetic domains and potential structures were interpreted from aeromagnetic data (Figure 4(A)). Despite good correlation between filtered magnetic data and mapped geological units, the available magnetic data have up to 500 km of line space, and therefore not enough spatial resolution to supplement local features from small-scale geological mapping. However, deep magnetic sources strongly responsible for the medium-scale structures, whereas the gammaspectrometric anomalies were preferred for tracing near-surface geological contacts (Figure 4(B)).

We used the ternary RGB composite image (R = K, G = eTh, B = eU, Figure 4(B)), in order to represent the total radiometric effect of each geological unit in the map. In this technique, K is represented in percentage and Th and U were converted to their equivalents for comparison to the K values (Ferreira et al., 2014). The radiometric maps presented in this study have shown good correlation with geological contacts between mudstones (K-rich) and carbonate units (Figure 4(B)), which led us to constrain lateral extension of these units. Examples of Capiru units with distinct geophysical signature are syenogranites of the Setuva core (intermediate magnetic anomalies and Th and
Th-K enrichment); and ferrouginous metasediments of the Jurui unit (high-K and highly magnetic anomalies). A distinct geophysical signature (bright yellowish colors on ternary map) occurs in the Apiai Terrane domain, northwestern of Lancinha Shear Zone.

4. Conclusions

Presented herein is a new edition of the Geological map of the Capiru Group at 1:150,000 scale. This contribution is the most up-to-date regional map, which integrates all the available published and unpublished data for these rocks. In addition, it incorporates multiple techniques to improve the knowledgebase of this unit. The map includes all the recent geological information delivered by the mapping project of the Capiru Project, Fiori (1985) and earlier maps, in addition to the Survey databases. In this new map six total lithostatigraphic units—in addition to the basement—were described and the main types of contacts and structural accuracy were revaluated. Throughout decades of study, significant progress in geological knowledge was made, which has provided the basis for new research targets in the area.

Software

All geologic data was first processed to compile a geodatabase using Esri ArcGIS. Geophysical data were processed using Oasis Montaj™ software. Outlined structures were imported to the Adobe Illustrator for layout design and key editing.

Open Scholarship

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This article has earned the Center for Open Science badge for Open Data. The data are openly accessible at https://doi.org/10.17632/mywdxfkw.1.

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Data availability statement

The GIS data that support the findings of this study are openly available in Mendeley data repository at doi:10.17632/mywdxkyfkw.1.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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