UNIVERSIDADE DE SÃO PAULO
INSTITUTO DE GEOCIÊNCIAS

Geotectonic study of the southeastern Dom Feliciano Belt in southern Brazil and its connections to the Punta del Este Terrane (Uruguay) and Pan-African mobile belts in southwestern Africa

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Advisor: Prof. Dr. Miguel Angelo Stipp Basei
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“Long is the way and hard, that out of Hell leads up to light.”

John Milton

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"In everyday life, there is more than meets the eye. To reach the depths of truth, we must drag the waters." Dimebag Darrel

RESUMO

As unidades supracrustais neoproterozoicas do Cinturão Dom Feliciano no sul do Brasil e leste uruguaio fornecem um registro da evolução tectônica do ciclo Brasiliano/Pan-Africano em termos de sedimentação, deformação, plutonismo e metamorfismo durante a assembleia do Gondwana ocidental. Foram adquiridos dados U-Pb e Lu-Hf em zircão de rochas metassedimentares e granitos do norte do Terreno Punta del Este (Domínio Jaguarão) e do Batólito Pelotas. Os complexos metassedimentares do Domínio Jaguarão possuem idades de zircão detrítico variando entre 3,2 a 0,7 Ga, com picos entre 2,2–1,7 Ga, 1,5–1,0 Ga e 1,0–0,7 Ga. As amostras do Complexo Herval, inserido no Batólito Pelotas, revelaram semelhantes idades de proveniência, com dois intervalos principais de 1,5–1,1 Ga e 1,0–0,7 Ga, com intervalos subordinados de 2,0–1,7 Ga e 2,8–2,4 Ga. A idade máxima de deposição dos complexos é restrita a populações de idade entre 700 e 650 Ma. Bordas metamórficas em zircão variam de 680 a 570 Ma. Os dados Lu-Hf dos zircões meso a paleoproterozoicas possuem valores de εHf(t) entre -10 a +10 e idades modelo paleoproterozoicas a arqueanas. Os valores de εHf(t) em zircões neoproterozoicos são predominantemente negativos (-15 a +5) com idades modelo meso a paleoproterozoicas. Dados U-Pb em zircão de granitos cálcio-alcalinos a peraluminosos, incluindo lentes intrusivas miloníticas nas sequências metassedimentares, apresentam idades de cristalização de 580-570 Ma, apontando para um magmatismo Ediacarano generalizado no norte do Terreno Punta del Este. Esses resultados demonstram a deposição sedimentar encerrou durante o desenvolvimento do metamorfismo e magmatismo relacionado ao arco criogeniano/ediacarano do cinturão Dom Feliciano. A escassez de rochas mesoproterozoicas na Província da Mantiqueira e áreas cratônicas próximas sugere que essas populações detríticas se originaram em rochas do sudoeste africano, provavelmente relacionados aos crátons Congo/Kalahari. Os dados U-Pb e Lu-Hf do Batólito Pelotas (arco-magmático) em zircões de rochas plutônicas com evidências de mistura e mistura de magma, bem como assimilação de rochas de embasamento, sugerem magmatismo polifásico relacionado a episódios de intenso magmatismo, potencialmente desencadeados por mudanças no ambiente tectônico. As análises U-Pb mostram idades de cristalização de xenólito de gnaisse granodiorítico em 691,5 ± 7 Ma, xenólito de microgranodiorito em 645,9 ± 3,7 Ma, monzogranito hospedeiro em 634,4 ± 4,4 Ma e sienogranito intrusivo em 620,1 ± 4,7 Ma, todos intrudidos por pegmatito sienogranítico em 60.9 ± 1,7 Ma. Outras análises foram realizadas em granito cálcio-alcalino (633 ± 4 Ma) e granito peraluminoso (609,6 ± 2,2 Ma). Os dados Lu–Hf destacam um intervalo de idade modelo variando de 1,7 a 1,3 Ga com valores de εNd entre -4 e 1, exceto para a amostra de pegmatito com idades modelo paleoproterozoicas a arqueanas (3,3-1,6 Ga) e valores de εNd entre -33 e 1. Os dados adquiridos enfatizam uma contribuição de fontes ligeiramente juvenis a crustais, com idades modelo variando principalmente do Estateriano-Orosiriano ao Mesoproterozóico. Os resultados apontam para um contexto geológico inicial extensional durante o Toniano (~800 Ma), com posterior deformação e metamorfismo regional ligado a estágios acrescionários e colisionais (690–570 Ma).

Palavras-chave: Geocronologia U-Pb, Isótopos Lu-Hf, Cinturão Dom Feliciano, Gondwana Ocidental

ABSTRACT

The Neoproterozoic supracrustal units of the Dom Feliciano Belt in southern Brazil and eastern Uruguay provide a record of the tectonic evolution of the Brasiliano/Pan-African cycle in terms of sedimentation, deformation, plutonism and metamorphism during the western Gondwana supercontinent assembly. From the northern Punta del Este Terrane (Jaguarão Domain) and Pelotas Batholith were acquired U-Pb and Lu-Hf zircon data from metasedimentary rocks and granites. The Jaguarão Domain metasedimentary complexes have detrital zircon ages ranging from 3.2 to 0.7 Ga, with prominent age peaks at 2.2–1.7 Ga, 1.5–1.0 Ga, and 1.0–0.7 Ga. The Herval Complex (Pelotas Batholith) revealed a similar provenance of detrital zircon ages, with two main intervals of 1.5–1.1 Ga and 1.0–0.7 Ga, and minor Paleoproterozoic (2.0–1.7 Ga) and Archean (2.8–2.4 Ga) ages. The maximum depositional age of the complexes is constrained to age populations between 700 and 650 Ma. Metamorphic zircon overgrowths range from 680 to 570 Ma. The Lu-Hf data from the meso- to Paleoproterozoic zircons have εHf(t) values between -10 to +10 and model ages from Paleoproterozoic to Archean. The εHf(t) values in Neoproterozoic zircons are dominantly negative (-15 to +5) with meso- to Paleoproterozoic model ages. U-Pb zircon data from calc-alkaline to peraluminous granites, including mylonitic intrusive lenses in the metasedimentary sequences, present crystallization ages of 580-570 Ma, which point to a widespread Ediacaran magmatism in the northern Punta del Este Terrane. These results demonstrate that sedimentary deposition ceased and underwent metamorphism during the development of the Cryogenian/Ediacaran arc-related magmatism of the Dom Feliciano belt. Given the scarcity of Mesoproterozoic rocks in the Mantiqueira Province and nearby cratonic areas, the obtained data suggest that these detrital populations originated in southwestern African rocks, most likely the Congo/Kalahari cratons. The Pelotas Batholith (Magmatic-arc domain) have U–Pb and Lu–Hf zircon data acquired from plutonic rocks with evidence of magma mixing and mingling, as well as assimilation of wall rocks, which suggest multi-stage magmatism related to flare-up episodes of magmatism, potentially triggered by changes in the tectonic setting. U–Pb zircon analyses yielded crystallization ages of granodioritic gneiss xenolith at 691.5 ± 7 Ma, microgranodiorite xenolith at 645.9 ± 3.7 Ma, host monzogranite at 634.4 ± 4.4 Ma, and intrusive syenogranite at 620.1 ± 4.7 Ma, all intruded by syenogranitic pegmatite at 606.9 ± 1.7 Ma. Other analyses were performed on calc-alkaline granite (633 ± 4 Ma) and peraluminous granite (609.6 ± 2.2 Ma). The Lu–Hf data highlights a model age interval ranging from 1.7 to 1.3 Ga with εNd values between -4 and 1, except for the pegmatite sample with Paleoproterozoic and Archean model ages (3.3-1.6 Ga) and εNd values between -33 and -1. Furthermore, the acquired data emphasizes a contribution from slightly juvenile to crustal sources, with model ages ranging primarily from Statherian-Orosirian to Mesoproterozoic. The geological context and isotopic results point to a prior extensional tectonic setting during the Tonian (~800 Ma), with regional deformation and metamorphism linked with accretionary and collisional stages (690–570 Ma).

Keywords: U-Pb geochronology, Lu-Hf isotopes, Dom Feliciano Belt, Western Gondwana.

SUMMARY

1. INTRODUCTION

1.1 Motivation for research and overarching goals

Studies on supercontinent tectonic settings and the evolution of Precambrian terranes have made significant progress in recent decades due to the contribution of geophysical and geochronological data through advances in the determinations of U-Pb crystallization ages and Lu-Hf isotopic composition in zircons, allowing a more accurate definition of geological domains. (Andersen, 2005, Condie, 2011; Cawood et al., 2012). The Neoproterozoic supracrustal units of the Dom Feliciano Belt (DFB) in southeatern South American Platform provide a record of the tectonic evolution of the Brasiliano/Pan-African cycle in terms of sedimentation, deformation, and metamorphism during the Western Gondwana supercontinent assembly. Indeed, the tectonic study of the DFB, which spans southwestern Brazil and eastern Uruguay over a range of ca. 1200 km (Basei et al., 2005; Philipp et al., 2016), is essential for understanding the stages of Precambrian supercontinents evolution.

The Western Gondwana (Figura 1.1) is result of the continental assembly during the Brasiliano and Pan-African cycles, whose records are found in Precambrian terranes from South America and southeastern Africa (Dalziel, 1997; Basei et al., 2005; Silva et al., 2005; Philipp et al., 2016; Hueck et al., 2018). Most paleogeographic reconstructions of Western Gondwana converge on the hypothesis that its formation process began with the breakup of Rodinia (ca. 840–750 Ma) and subsequent convergence of continental blocks (ca. 720-550 Ma), which included the Rio de La Plata, Luis Alves, Kalahari, and São Francisco-Congo cratons (Basei et al., 2008; Oyhantçabal et al., 2009; Saalmann eta al., 2010; Frimmel, 2018; Hueck et al., 2018). While this general evolution is well accepted, many details are still controversial, such as subduction direction and origin of some cratonic blocks (Frimmel et al., 2011; Oyhantçabal et al., 2011; Chemale, 2012; Basei et al., 2018; Oriolo et al., 2019; De Toni et al., 2020; Hueck et al., 2022; Silva Lara et al., 2022). However, recent studies have challenged this tectonic setting as a whole, revisiting the prior concept of an intracontinental orogen (Torquato and Cordani, 1981; Porada, 1989). These studies support the model that Brasiliano/Pan-African basins developed in an intracontinental setting and subsequently underwent inversion, leading to the formation of collisional belts between ca. 650-600 Ma, followed by transcurrent tectonics between ca. 600-560 Ma. (Meira et al., 2015; Konopásek et al., 2020; Percival et al., 2021).

The idea of the present study arose during the geological mapping activity of the Sudeste do Rio Grande do Sul project (Cruz, 2019) in an area that has historically been described as part of the Pelotas Batholith, an extensive granite massif that extends across the eastern part of the DFB. However, some previous works have pointed to the presence of a "new" tectonic block in the southern segment of the batholith. CPRM geophysical maps (CPRM, 2010) show an extensive magnetic lineament with ENE-WSW orientation that separates two distinct geophysical domains in this sector. Ramos and Koester (2014) based on geophysical maps and studies of metaultramafic rocks, highligh the area as likely block boundary.

In a mapping report for the Curral de Pedra and Passo São Diogo maps (Iglesias et al., 2018), it was concluded that part of the area covered by the projects is a different geological domain, which they termed Jaguarão Terrane. The area contains a sequence of metasedimentary rocks that form a lithological association very different from that found in the Pelotas Batholith and very similar to those found in the Punta del Este Terrane (Preciozzi et al., 1999; Basei et al., 2005), another segment of the DFB.

The primary purpose is to characterize the boundary and relation between the Pelotas Batholith and northern Punta del Este Terrane, in this research referred to as the Jaguarão Domain (Fig. 1.1). With emphasis on newly acquired isotopic data, supported by field work, thin section description, along with intepretation of whole-rock chemistry and geophysical maps. This study aimed at exploring through U-Pb and Lu-Hf zircon analyses the provenance sources of the supracrustal metamorphic complexes of the Jaguarão Domain. Additionally, to characterized the regional metamorphism and related magmatism on the domain were also acquired isotopic data from mylonitic leucogranites and porphyritic plutons that crosscut these complexes.

Futhermore, new zircon U–Pb and Lu–Hf SHRIMP/LA-ICPMS data were obtained in granitoids of the Pinheiro Machado Suite, the largest unit of the Pelotas Batholith, to provide new insights or refine existing knowledge about the magmatism of DFB. The suite exhibits evidence of magma recharges, assimilation of xenoliths, mingling, and mixing with mafic magmas, as observed in previous studies (Philipp et al., 2002; Philipp and Machado, 2005; Loureiro et al., 2021). Along with the isotopic data, interpretation of the whole-rock chemistry was used to support the findings.

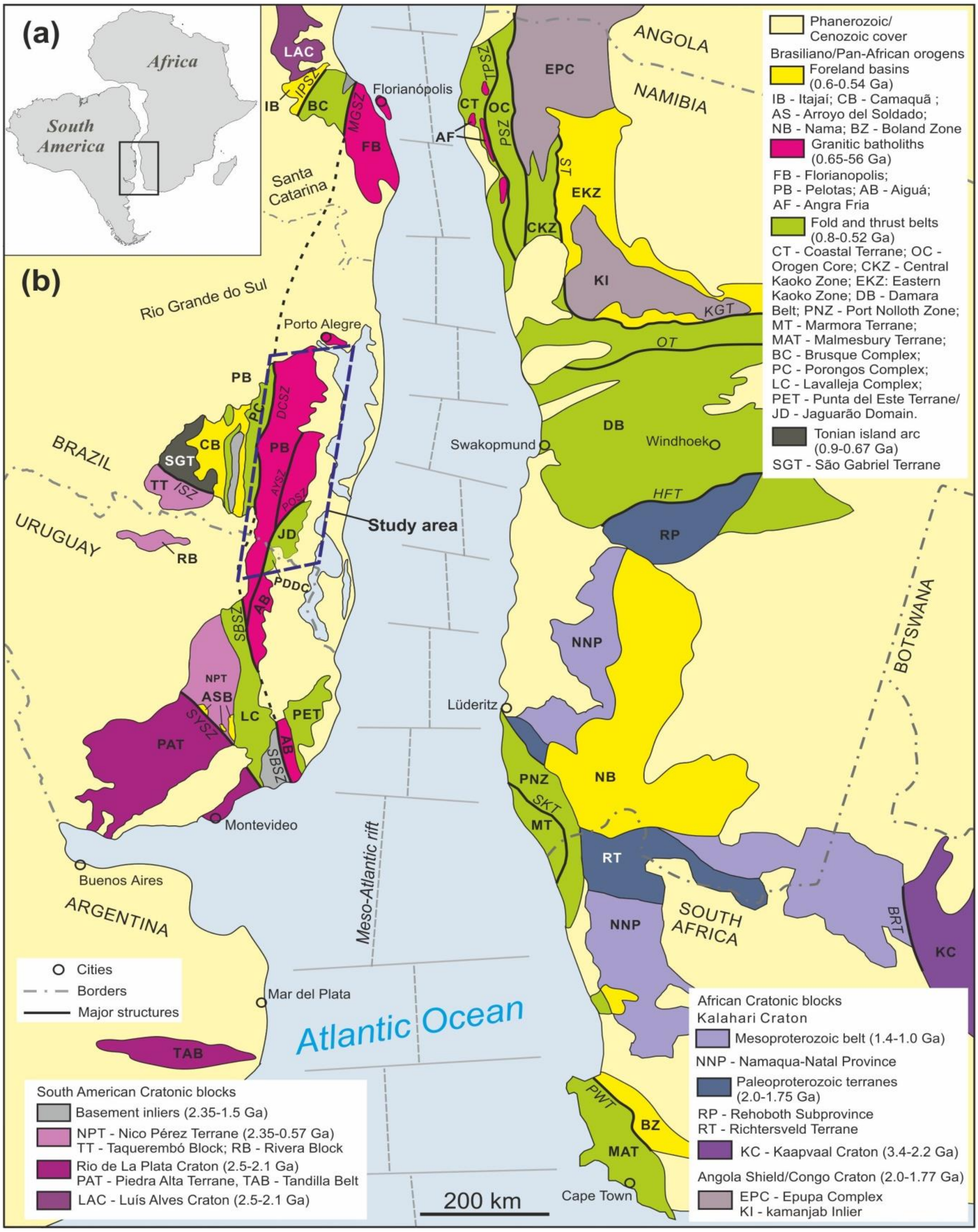

Figure 1.1: A) Reconstruction of the South American and African continents. B) Former Western Gondwana terranes framework with outlined study area (modified from Basei *et al*, 2008, Goscombe et al, 2018, Frimmel, 2018, Hueck et al, 2018). Shear zones (SZ): IPSZ - Itajaí-Perimbó; MGSZ - Major Gercino; ISZ - Ibaré Shear Zone. DCSZ - Dorsal do Canguçu; SBSZ - Sierra Ballena; TPSZ - Three Palms; PSZ – Purros; ST - Sesfontein Thrust; KGT - Khorixas-Gaseneirob Thrust; OT – Otjorongo Thrust; HFT - Hakos Frontal Thrust; SKT – Schakalsberge Thrust; PWT - Piketberg-Wellington Thrust; BRT – Blackridge Thrust.

1.2 Dissertation outline

This doctoral dissertation has been organized into six main chapters. Chapter 1 introduces the motivation, objectives and implications, as well as the geotectonic context of the studied area and presents the overall struture of the dissertation. Chapter 2 includes a brief review of the applied methodology of the proposed research. Chapters 3, 4, and 5 present the results obtained during the research, which were organized and included in three manuscripts of scientific papers. The first manuscript is under review by the International Geology Review journal from Taylor & Francis editorial company, and the other two are currently available in Precambrian Research and Journal of South American Earth Sciences from Elsevier academic publishing company.

Chapter 3 presents the paper "Unveiling the stratigraphy of the northern Punta del Este Terrane (Jaguarão Domain) and its role in the Neoproterozoic tectonic evolution of the Dom Feliciano Belt (southern Brazil and Uruguay)". The manuscript describes the basic stratigraphy of the so-called Jaguarão Domain through outcrops and thin section descriptions. The understanding and drawing of regional structures are accomplished by structural analysis based on fieldwork and geophysical maps (magnetometric and gravimetric). Additionally, LA-ICPMS U-Pb zircon and whole-rock chemical analyses were carried out to characterize the widespread peraluminous magmatism in the domain.

The paper "Insights into the evolution of the southeastern Dom Feliciano Belt and its connection to the Pan-African Orogeny based on new U-Pb and Lu-Hf zircon data" is in Chapter 4. The manuscript presents a set of results from LA-ICPMS U-Pb and Lu-Hf in zircon, including provenance analyses of metasedimentary sequences and crystallization ages of the granites that occur as intrusive lenses or plutons. To understand the geodinamics of the Jaguarão Domain are carried out Hf isotopic studies towards the most representative U-Pb zircon ages. All results have been included in the dataset of the Pan-African/Brasiliano belts from southeastern Brazil, eastern Uruguay and southwestern Africa to make the correlations and interpretations on the tectonic events that involved the domain in the context of Western Gondwana assembly.

Chapter 5 carry the paper intitled "Potential flare-ups and lulls in the multi-stage magmatism of the Dom Feliciano Belt, southern Brazil: Evidence from geochemistry and isotopic data". The last manuscript brings U-Pb and Lu-Hf zircon analyses by SHRIMP and LA-ICPMS methods obtained primarily on samples from a single outcrop with features of magma mixing, assimilation of wall-rock, and late intrusive magmatism. The new isotopic results were compared with previously published data from the Pelotas Batholith, which, togeter with whole-rock chemistry from SGB-CPRM (Brazilian Geological Survey), allows for the inference of potential events of intense magmatism associated with changes in the Dom Feliciano Belt then-ongoing tectonism.

Finally, Chapter 6 summarizes the results and discussions from the former chapters in a brief integrative conclusion of the dissertation. Furthermore, the remaining questions have been identified as potential future research topics. Emphasizing gaps and alternative techniques to generate strong outcomes for assessing the tectonic evolution of the Dom Feliciano Belt through the Western Gondwana assembly processes.

2. MATERIAL AND METHODS

2.1 Field work and general aspects of the geological units

The results presented in the papers (Chapters 3 to 5) are based on the problems identified in the mapping work of the Sudeste do Rio Grande do Sul project (Cruz, 2019), in which, supported by the interpretation of aeromagnetic and gravimetric data, the high-deformation zones are traced, as well as the definition of the central units of the Jaguarão Domain and the southern Pelotas Batholith. Subsequently, the most representative outcrops were selected to collect material for petrographic, chemical and geochronological analysis. The fieldwork, accompanied by advisors, comprises the description of 55 outcrops focusing on the following key units of the study area:

- The Arroio Telho and Arroio Grande metavolcanosedimentary complexes were describe in terms of deformation phases, metamorphism and correlations with the La Micaela Schists and La Tuna Serpentinites from Paso del Dragon (Uruguay).
- The Herval Complex, mainly composed of quartzites and subordinately of schists and metaplutonic rocks, is understood as a mega-xenolith within the Pelotas Batholith and was selected to investigate its correlation with the above complexes.
- The Três Figueiras Suite, which includes intrusive peraluminous granites, is mainly located at the boundary of the Jaguarão Domain and the Pelotas Batholith. Additionally, the Capão do Leão, Chasqueiro and Bretanha granites were also described with the objective of understanding the latter’s magmatism and deformation in the Jaguarão Domain.
- The Pinheiro Machado Suite, the largest suite of the Pelotas Batholith, focused on the Prainha dos Melões outcrop, which shows a complex relationship between xenolith assimilation and tardi-intrusive magmatism, which could be understood as a fractal of the

magmatic processes in the batholith as a whole.

2.2 Microscopic Petrography and whole-rock chemical analysis

The researcher used the facilities of the SGB-CPRM (Laboratory of Porto Alegre) to prepare the 150 thin sections, and carried out the prior treatment of the 160 samples for whole-rock chemical analysis, which involved fragmenting and pulverizing the samples to achieve a particle size less than 200 mesh. The petrographic analyses of the thin sections allowed the identification of the protoliths based on the recognition of primary structures, textures and the characterization of microstructures and metamorphic conditions.

The multi-elemental analyses were carried out at SGS GEOSOL - Laboratory LTDA, (Vespasiano, Brazil). The method applied included lithium borate fusion and determination by X-ray fluorescence for major oxides and ICP-MS for minor elements and REEs (Rare Earth Elements). The acquisition of whole-rock data had the initial goal of supporting the SGB-CPRM projects from Cruz, 2019, and Takehara and Laux, 2019. The geochemical diagrams were created using the GCDkit program (Janoušek et al., 2006), using the whole-rock chemistry data above quoted in addition to data gathered from academic papers from Klein et al., 2018, Vieira et al., 2016 and Silva et al., 2016. The whole-rock chemical analysis tables are presented in the Appendix of Chapters 3 and 5.

2.3 Geochronological and isotopic analysis of rocks

Once the sampling sites were selected, the work of sample preparation and isotopic analysis was carried out. Details of the procedures used for both preparation and analysis are given in the appendices to the papers in Chapters 3 to 5. Zircon age determinations were performed on 6 samples from the Arroio Telho, Arroio Grande and Herval complexes. For the granitoids, 12 U-Pb geochronologic analyses were performed. Lu-Hf isotopic studies were carried out on 4 samples of metasediments and 7 samples of granitoids. A brief bibliographical background of the geochronological studies used in this thesis is given hereafter.

2.4 Isotope geology

Estimates of the Earth's age and its rocks have gone through a long and contentious historical process, with attempts to obtain ages from rocks, such as that of James Hutton and collaborators in the 18th century, who arrived at an estimate of 700 Ma as the time elapsed since the Cambrian by calculating the sedimentation rate of different types of strata. With the discovery of radioactivity by Becquerel (1896), significant progress in understanding and applying the phenomenon as a technique for dating rocks began, with Rutherford (1905) producing the first acknowledged result by examining the decay of the element Radium to

Helium. Since then, a number of techniques in the field of isotope geology have been developed as a chronological tool, including the Rb-Sr and Sm-Nd methods, among others, but with a strong emphasis on the U-Pb method.

2.4.1 The U-Pb method and zircon

The U-Pb method is the most robust geochronological tool and is based on the principle of radioactive decay of the U, Th, and Pb isotopes. Isotopes are elements that have the same atomic number (protons) but a different mass number. Radiogenic isotopes have a decay time when they lose half their mass and transition from a parent element to a daughter element, and this elapsed time is known as their half-life ($T_{1/2}$). Zircon ($ZrSiO_4$) crystallizes with a high U concentration, has low Pb diffusion, and is incompatible with common lead. It is a widely distributed accessory mineral in the earth's crust, including igneous, sedimentary, and metamorphic rocks, as well as meteorites and lunar rocks. Zircon is chemically resilient and refractory, withstanding weathering, transport, diagenesis, and, to a lesser extent, metamorphism. Because of these properties, zircon is the primary material to employ the U-Pb technique (Hanchar & Miller, 1993; Dickinson, 1995).

The decay of U into two series of Pb isotopes produces three separate geochronometers, $^{238}U/^{206}Pb$, $^{235}U/^{207}Pb$, and $^{207}Pb/^{206}Pb$, which should all yield the same age value for the material analyzed. Wetherill (1956) proposed the concord diagram, which puts these ages into a single diagram and makes it easy to comprehend potentially discordant data. The curve of the diagram is defined by systems with concordant U-Pb ages. The isotopic compositions of the items to be studied are thus compared with the concordance curve, allowing their age to be estimated. Geochronometers generate concordant ages when the mineral to be dated has stayed closed to U loss and the corrections for Pb initially integrated into the mineral are clearly specified, and the results can align on a straight line or a route of Pb loss, known as a discordia line (Faure 1986).

The Concordia Age (Ludwig, 1998) exists when the ratios $^{207}Pb/^{235}U$, $^{206}Pb/^{238}U$, and $^{207}Pb/^{206}Pb$ are alike within uncertainty estimates, or when the corresponding U/Pb and Pb/Pb ratios have error ellipses that overlap the Concordia curve within the 95% certainty estimate (e.g. Fig. 2.1). The Tera-Wassenburg diagram (Wendt, 1984) is another type of diagram for displaying isotopic data (e.g. Fig. 2.1). The graphic was designed to make it easier to obtain data from younger rocks. Where the abscissa is the $^{238}U/^{206}Pb$ ratio, and the ordinate is the $^{207}Pb/^{206}Pb$ ratio. The individual findings that form a cohesive grouping are organized along a simple mixing line (with the common Pb) in this concordance, and the age is derived by crossing the mixing line (discordia) with the abscissa. This form of graphic depicts the lower intercept age and has the main advantage of allowing the identification of common ^{204}Pb correction when measured in little amounts (Parrish & Noble, 2003).

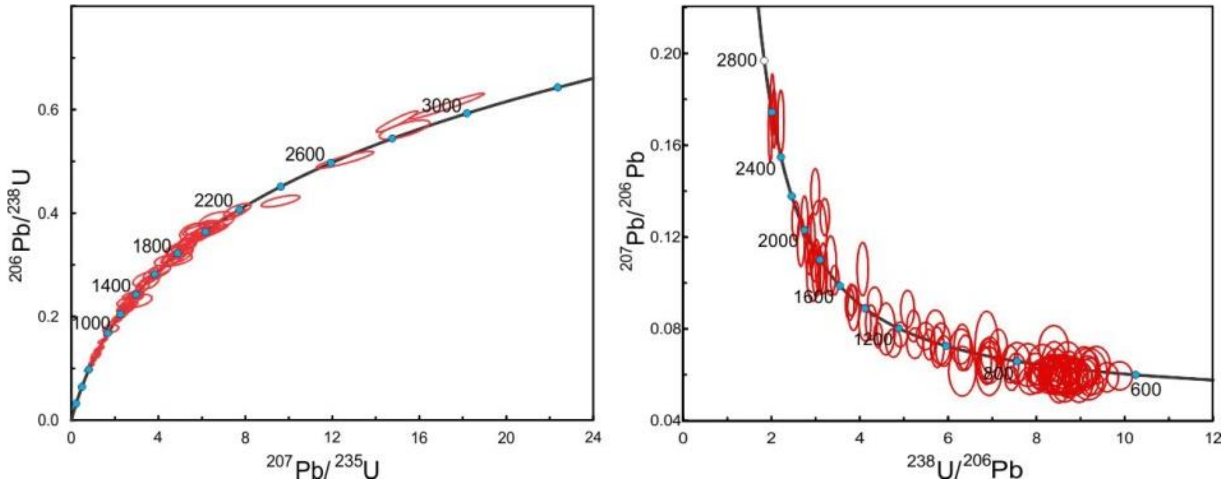

Figure 2.1: A) Wetherill Concordia diagram. B) Tera-Wasserburg Concordia diagram. The diagrams used as examples are found within Chapter 04.

2.4.2 *The Lu-Hf Method in zircon*

In addition to the U-Pb ages obtained in zircon, hafnium (Hf) isotope measurements can be obtained, which indicate the relative composition of the source of the mineral, whether there was a greater contribution of material of mantle origin (juvenile) or material from recycled continental crust (Harrison et al. 2005). Hf isotopic values are used in a calculation called Hafnium Epsilon (εHf), which takes into account the known average value of the element in the CHUR (Condritic Uniform Reservoir), assuming that positive values correspond to mantle-derived magmas and negative values correspond to crustal magma-derived rocks.

2.4.3 *Geochronological data acquisition equipment*

The determination of the ratio of radioactive isotopes and radiogenic isotopes involves the separation of isotopes according to their mass. Mass spectrometry originated in 1913 with the development of the first magnetic field-based spectrometer (Dickin, 1995). Thermal ionization, plasma induction, and ion beam source are three widely used methods in isotope geology and geochronology. LA-ICP-MS (laser ablation inductively coupled plasma mass spectrometry) and SHRIMP (sensitive high-resolution ion microprobe) are the most regularly used spectrometers today. Both provide ages for a specific zone of the grain with high analytical accuracy and are widely used for U-Pb and Lu-Hf ages in zircon and monazite minerals. In general, these mass spectrometers consist of an energy emitter that extracts material from the sample and then passes through an electrostatic analyzer and magnetometer system where the isotopes that reach the multicolectors are separated and ratio readings are taken.

2.4.4 Zircon imaging techniques

The interpretation of the analytical results obtained by SHRIMP and/or LA-ICP-MS techniques involves the observation of the structures and internal characteristics of the minerals analyzed, aided by images obtained by cathodoluminescence (CL) or scanning electron microscope (SEM) (Rubato & Gebauer, 1998; Silva, 2005). Image analysis enables the recognition of different domains based on the textural pattern presented by the zircon, avoiding heterogeneous and fractured zones within the grain, thereby improving control over the acquisition and interpretation of geochronological data. Cathodoluminescence images indicate the relative uranium concentration of zircon by luminescence intensity (Rubatto & Gebauer, 1998). Magmatic textures are characterized by oscillatory zoning caused by alternating U-rich and Pb-poor halos of high and low luminescence, respectively. Metamorphic zircons generally lack oscillatory zoning and exhibit a homogeneous internal texture.

2.4.5 Detrital zircon provenance studies

U-Pb dating of detrital zircons from siliciclastic metasedimentary rocks is a widely used tool for the geological reconstruction of metamorphic terrains that have undergone at least one or two tectonic events, helping to understand the geological evolution of mobile belts and paleocontinents (Froude et al., 1983; Condie et al., 2009). The LA-ICP-MS is the most suitable equipment for detrital zircon provenance studies because it allows the spot analysis of a large number of zircons in a relatively short time (an average of 20 grains per hour session). Dating a significant number of zircons ensures that a proper provenance analysis is carried out. According to Vermeesch (2004), a value greater than 100 grains is appropriate so that no fraction containing at least 5% of the total sample population goes undetected, thereby achieving a 95% confidence level. Provenance ages are critical for understanding crustal evolutionary processes (Harrison et al., 2005).

Whole-rock Sm-Nd analyses are useful in these investigations, but often yield mixed ages, leading to misinterpretation. In these circumstances, combined U-Pb and Lu-Hf isotopic analyses in detrital zircons allow the distinction of grains of the same crystallization age but derived from crustal areas of different mantle-derived ages. As a result, it is possible to construct graphs that plot the εHf parameter on the ordinate against the crystallization age on the abscissa as an indication of domains of different crustal residence ages in a particular section of the crust.

Patterns of age signatures of detrital zircons generally reflect the tectonic setting of the basin in which they were deposited. Convergent plate margins (accretionary tectonics) are characterized by large proportions of zircons with ages close to the basin depositional interval, in this case the forearc, backarc and trench zones (Condie et al., 2009). Whereas basins formed from continental and extensive collisional environments contain higher proportions of zircons with ages older than the time of deposition, reflecting the evolutionary history of the bedrock on which they were formed (Cawood et al., 2012, 2013).

However, magmatism volume and preservation potential vary significantly with tectonic setting (Hawkesworth et al., 2009), affecting the amount of zircon present in the sedimentary record. In convergent plate settings, large volumes of magma are generated, but with low preservation potential in the geologic record (Scholl and Von Huene, 2009). Continental collision-dominated settings produce small magmatic volumes, which are melting products of pre-existing crust (Hawkesworth et al., 2010), but their preservation in the geologic record is favored during the supercontinent formation cycle, resulting in a larger amount of preserved zircons. Extensive settings generate variable amounts of magma (White, 1992), but with a greater occurrence of mafic magmatism (Storey, 1995), resulting in a more restricted generation of zircons. Furthermore, these rocks are more susceptible to erosion, resulting in reduced preservation potential. Thus, the magmatic age record is dominated by periods of final supercontinent formation, not because of massive crustal generation, but because it provides a suitable setting for the preservation of rocks generated by continental collisional magmatism.

3. CONCLUSIONS AND REMARKS

The Jaguarão Domain (JD) is the northern segment of the Punta del Este Terrane (PET), which occurs on the eastern edge of the DFB in contact with the Aiguá and Pelotas batholiths (650-550 Ma). Gravimetric geophysical maps distinguish the JD as a high density domain compared to the granitic batholith areas. It is also observed in the geophysical (aeromagnetic) maps that the main structures (Pedro Osório, Arroio Grande and Cerro Amaro shear zones) partially mark the boundaries of the JD.

Provenance data for the JD metasedimentary units showed approximately 80% zircon crystals with Meso- to Paleoproterozoic ages, distinguishing these units from similar rocks found in the DFB where Neo- and Paleoproterozoic ages predominate (e.g., Porongos and Lavalleja complexes). Geologic similarities and zircon provenance patterns strongly support the correlation of the Arroio Telho/Arroio Grande and Herval complexes of Brazil with the Paso del Dragon/Cerro Olivo complexes of Uruguay and the metasedimentary sequences of southeastern Africa.

The Lu/Hf isotopic data from JD present model ages between 3.6 – 1.0 Ga and εHf values predominantly around -10 to +10, which implies mixing sources originated mainly from the assembly processes of the Columbia (2200-1500 Ma) and Rodinia (1400-950 Ma) supercontinents. Tectonic and metamorphic similarities, plus the zircon provenance pattern and isotopic data, support the correlation of the JD/PET with the western domains of Gariep and Kaoko belts units (Africa).

The data set of crystallization and provenance ages places the JD in a more reliable setting as a rift-related basin on the western border of the Namaqua-Natal Belt that underwent a tectonic inversion after the collision (~660 Ma) between the African and South American domains. The metamorphic conditions reached a peak around 650-630 Ma. Then, around 570 Ma, a second thermal-metamorphic event promoted partial melting of the metasedimentary pile, resulting in widespread peraluminous magmatism in the JD and southernmost Pelotas Batholith (PB).

The emplacement of the DFB granitic batholiths marked an important change in the provenance age scenario. The input of late-Mesoproterozoic and Tonian material disappears in syn- to post-orogenic sequences of the western branch of the DFB (e.g., upper sequence of Porongos Complex, Arroyo del Soldado, and Camaquã basins). In contrast, the eastern sequences (e.g., Rocha Formation) show that the provenance did not end after the accretionary-collisional setting. The breakup of the Pangea supercontinent resulted in the current JD arrangement, located in southeastern South America as a remnant of the orogenic systems found in southwestern Africa.

The Prainha dos Melões outcrop is a fractal evolution of the Pinheiro Machado Suite and the PB magmatism as a whole. The differentiation processes assert the influence of partially assimilated older rocks and mafic magmas through new magmatic pulses. There is also recharge of the magma chamber in the form of dykes and sills. Whole-rock chemistry shows that southeastern DFB magmatic suites are primarily classified as I-Type peraluminous granites, with some suites being S-Type peraluminous. The chemistry diagrams depict magmatism with a diversity of sources and orogenic signatures, primarily related to a collisional to post-collisional setting with a major contribution from crustal sources.

The U-Pb zircon ages support a scenario in which the magmatism evolved in pulses around 690 Ma, 645 Ma, 635 Ma, 620 Ma, and 610 Ma. The Hf isotopes from the same samples show T_{DM} (t) ages with the main interval of 1.7-1.3 Ga and εHf values ranging from 1 to -4. These results are similar to those found in the metasediment data, indicating that African crust had an important contribution to the isotopic signature of arc-magmatism. The gathered U-Pb dataset shows well-defined intervals of magmatic pulses, lasting on average 10 Ma, in 660-650 Ma, 640-630 Ma, 620-610 Ma, 600-590 Ma, and 580-560 Ma. The main peak of the U-Pb ages falls within the 620-610 Ma interval, which overlaps the average age of the intrusive peraluminous granites in the western boundary of the PB and is associated with the partial melting of the Várzea do Capivarita Complex.

Based on the obtained results and conclusions, I made the following reccomendations:

- The development of thermodynamic modeling, which can be done by carrying out whole-rock chemistry in combination with chemical analysis of the minerals in the metamorphic paragenesis of the metasedimentary complexes, in order to generate pseudo-sections to quantify the P (pressure) and T (temperature) parameters of metamorphism.
- Perform a refined processing of the geophysical data to generate products such as magnetic deconvolution and gravimetric inversion profiles, to better delineate geophysical anomalies, as weel as the depth and angle of regional structures, related to tectonic block boundaries.
- Increase the coverage of Lu-Hf data on the magmatic suites of the batholith. There is a reasonable amount of Sm-Nd data in the literature, but as they are isotopic results on whole-rock it limits more refined interpretations on the sources and evolution of magmatism.

- Conduct a refined isotopic study on the rocks of the Matarazzo Complex, another mega-xenolith of metasedimentary rocks within plutonic rocks, in order to improve the correlations of these rocks with those present in this study.

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