

UNIVERSIDADE DE SÃO PAULO

INSTITUTO DE GEOCIÊNCIAS

The Campinas-Jaguariúna Sill, NE Paraná Continental Flood Basalt  
Province, Brazil: insights on the mechanisms of emplacement and  
differentiation from geochemical and magnetic data

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Dissertação apresentada ao Programa  
Geociências (Mineralogia e Petrologia) para  
obtenção do título de Mestre em Ciências

Área de concentração: Petrologia ígnea e metamórfica

Orientador: Prof. Dr. Valdecir de Assis Janasi

SÃO PAULO

2022

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Dissertação de Mestrado

**Nº 891**

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SÃO PAULO  
2022

## **Abstract**

The Paraná Continental Flood Basalt Province (PCFB), one of the largest magmatic provinces in Planet Earth, is composed of lava flows, dike swarms and sills that occupy thousands of kilometers across central-eastern South America. The Campinas-Jaguariúna Sill (CJS) is a large (<50 m thick and >100 km<sup>2</sup>) diabase intrusion showing frequent medium to coarse-grained gabbroic segregations and was emplaced at the interface between the Precambrian basement and sedimentary rocks in the northeastern Paraná Basin. This paper applies aeromagnetic and geochemical modeling to help understand the emplacement mechanisms and petrological evolution of the CJS. Magnetic field filtering techniques demonstrates that the CJS continues for tens of kilometer in the subsurface; analogous features are shown to be associated with other neighbor diabase occurrences, creating lobe-shaped structures that seem to freeze their original geometry and are not fully exposed by the current erosion levels. Petrological modeling indicates that the parental magma of the CJS was emplaced at ~1 kbar, 1000 ppm H<sub>2</sub>O and oxygen fugacity near FMQ-1. The gabbroic segregations, exposed as cm- to dm-sized sheets and eye-shaped lenses, are more evolved than the host diabase and can be shown by geochemical modeling to correspond to residual melts formed by crystal fractionation in a closed-system. The parent magma of the CJS is akin to the more primitive Paranapanema magma-type of the PCFB and we tested the possibility that sills intruding upper sedimentary layers may be part of a single sill complex. For this purpose we used geochemical data from the well-studied Limeira Sill, which is akin to the more evolved Pitanga magma-type. Our modeling shows that under crystal fractionation in the representative system condition a CJS starting compositions cannot generate the Limeira rocks.

**Keywords: Gabbroic melt segregation; Sill emplacement; Paraná Continental Flood Basalt Province**

## Resumo

A Província Magmática do Paraná (PMP), uma das maiores províncias magmáticas no Planeta Terra, é composta por derrames de lava, enxames de dique e soleiras que ocupam milhares de quilômetros na porção centro-leste da América do Sul. A Soleira Campinas-Jaguariúna (CJS) é uma grande intrusão de diabásio (<50 m de espessura e >100 km<sup>2</sup>), mostrando frequentes segregações gabróicas de granulometria média a grossa, que foi alojado na interface das rochas do embasamento Precambriano e das rochas sedimentares no nordeste da Bacia do Paraná. Este estudo aplica modelamentos aeromagnéticos e geoquímicos para compreender os mecanismos de alojamento e evolução petrológica do CJS. Técnicas de filtragem do campo magnético demonstram que o CJS continua por dezenas de quilômetros em subsuperfície. Padrões análogos estão associados com outras ocorrências de diabásio vizinhas, gerando estruturas em formas de lobos que aparentam registrar a geometria original de corpos que não estão expostos pelo nível de erosão atual. Modelamentos petrológicos indicam que o CJS foi alojado a 1 kbar, com 1000 ppm de H<sub>2</sub>O e fugacidade de oxigênio próxima de FMQ-1. As segregações gabróicas, expostas como camadas ou lentes centimétricas a decimétricas, são mais evoluídas que o diabásio hospedeiro e modelamentos geoquímicos indicam que correspondem a líquidos residuais formados por cristalização fracionada em um sistema fechado. O magma parental do CJS assemelha-se ao tipo Paranapanema da PMP e foi testada a possibilidade de soleiras intrudindo sequências sedimentares mais rasas fazerem parte de um único complexo de soleiras. Com este intuito, foram usados dados geoquímicos de um corpo já estudado em detalhe, a Soleira Limeira, que se assemelha ao magma mais evoluído do tipo Pitanga. Nosso modelo mostrou que rochas do Limiera não podem ser geradas por fracionamento do magma parental do CJS nas condições representativas encontradas para o sistema.

**Palavras-chave:** Líquidos segregados gabróicos; Alojamento de Soleira; Província Magmática do Paraná

# **1 - Introduction**

## **1.1 – Introduction and justification**

The Campinas-Jaguariúna Sill (CJS) is a large diabase body (>50 m thick, exposed for ca. 100 km<sup>2</sup>) related to the sills that occurs in the NE portion of the Lower Cretaceous Paraná Magmatic Province (PCFB), in the state of São Paulo, Brazil. This sill is known in the literature for host expressive gabbroic segregations (Oliveira et al., 1998) and was sampled in regional studies (Oliveira et al., 1998; Ernesto et al., 1999; Machado, 2005), but the origin of the melt segregation structures and the stratigraphic relationships were not addressed in detail. The sill was emplaced at the boundary between the crystalline basement of Precambrian age and the sedimentary rocks of the Paraná Basin. Possibly due to its expressive volume and depth of emplacement, and consequent slow cooling rates, the CJS preserved important structures of melt segregation in form of subhorizontal lenses and eye-shaped pockets of medium-to coarse-grained mesocratic rocks of gabbroic composition that are injected in the host fine-grained diabase, mostly at the upper parts of the sill. Similar segregations have been reported in recent works on thick basaltic flows in the PCFB (Oliveira et al., 2020, Gomes et al., 2022) and fractionated, coarse-grained gabbros and monzogabbros are recognized as more differentiated rocks derived from diabase in intrusive bodies occurring near the CJS (Limeira Sill; Oliveira and Dantas, 2008; Farias, 2012, Lino et al., 2018, Lino and Vlach, 2021). In this scenario, the CJS offers an excellent opportunity to study the mechanisms of melt segregation in large basaltic bodies and their geochemical and morphologic relationships with regional analogous PCFB occurrences. Our observations can be used to understand the process of magma evolution and emplacement of large sills in Continental Flood Basalt Provinces (CFB). We also used aeromagnetic surveys to investigate the geometry of the CJS and neighbor diabase occurrences. Our results can be useful to several research areas,

including oil exploration (Araújo et al., 2005; Teixeira et al., 2020); mineralization and supplies for civil construction (Evans, 2009; Arena et al., 2014).

## **1.2 – Objective**

The emplacement process and geochemical evolution of subvolcanic bodies are governed by their composition, volatile content, host rocks and several processes of magma differentiation. These processes have been subject of a wealth of studies in rocks of basaltic composition, but not many studies are published on sill geometry and their in-situ magmatic differentiation processes in the PCFB (e.g., Costa et al., 2016, Lino et al., 2018). The main objectives of this research are to characterize the morphology of the CJS and neighbor occurrences in the eastern part of the state of São Paulo using geophysical approach as well as establish the magmatic evolution path that generated the fractionated bodies of gabbro by geochemical modeling. The techniques were used to investigate relationships between the CJS and Limeira Sill to elucidate mechanisms of sill emplacement in the northeastern PCFB. Our specific objectives consist in:

- Register the main structural patterns, stratigraphic relationships and textural variation across the sill.
- Characterize the petrographic differences between gabbroic segregations and host diabase.
- Use whole-rock and mineral chemical data to infer the physico-chemical conditions of magma emplacement and generation of melt segregations in the CJS.
- Use aeromagnetic data to identify the morphology of the CJS and neighbor subvolcanic occurrences intrusive in sedimentary rocks in the northeast PCFB.

### **1.3 - Structure of dissertation**

The present work presents an integrate investigation in the CJS, aiming provide insights for emplacement and magmatic evolution of diabase sills in the PCFB. This dissertation is divided in five chapters. This chapter (I) presents an introduction to the study object and objectives of this research. Chapter II is based on a compilation of fundamental hypothesis about the origin of Large Igneous Provinces (LIPs), focusing Continental Flood Basalts. Chapter III details the methodologies applied in the magnetic and geochemical modeling. Chapter IV is formatted as a paper and presents the main results obtained in the research. Chapter V summarizes the main conclusions of this work and future research that will be developed with data already obtained. Data tables with geochemical data and scanning electron microscopy images are presented in Appendices A, B, C, D, E and F.

### **2 - Concluding remarks and next steps**

The CJS is a thick (>50m) diabase intrusion apparently exploiting the interface between the Precambrian basement rocks and the basal layers of the Itararé Subgroup in the northeast Paraná Basin. The reasons for preferential emplacement of magma at this specific discontinuity is not fully understood, and can be result of a great magmatic pile weight and tensile strength barriers (Pitanga sills) that inhibited (probably) late-intruded sills as the Paranapanema-type CJS to reach higher stratigraphic levels. It is possible that this also influenced emplacement of late Pitanga-type sills because many sills that were emplaced at the basement-basin boundary to the NE of the CJS are of this type.

Lobe and circular shapes shown in aeromagnetometric surveys in the area of occurrence of basaltic rocks intrusive into sedimentary rocks of the Paraná basin are probably

related to partially non-exposed PCFB sills, thus inferred to be much more extensive than the mapped bodies. Magnetic modeling demonstrates that the PCFB subvolcanic bodies in this region are part of large sill complexes intruding different Paleozoic formations. Geochemical modeling presented in this work show, however, that no cogenetic relationship exists between the CJS (Paranapanema-type) and the Limeira Sill (Pitanga-type), which intrudes upper sedimentary sequences. Therefore, at least two magma pulses should have formed the northeast Paraná Basin sill occurrences. Paleomagnetic data presented by Ernesto et al. (1999) show that Pitanga-type sills occurring to the north of the study area show both normal and reverse polarity, which is indicative that at least three pulses of sill emplacement must have occurred in this region, two of Pitanga affinity and one of the Paranapanema magma-type, represented by the CJS and a sill occurrence in the region of Porto Feliz, to the SW (Machado, 2005).

The CJS is composed of diabase and sheets/pockets of gabbroic melt segregations, structures that are indicative of magma differentiation within a relatively large basaltic chamber. Our modeling allows estimate 1 kbar (3 km depth), FMQ -1 and 1000 ppm H<sub>2</sub>O (0.1 wt%) as the prevailing condition for the CJS magmatic evolution. Crystal fractionation modelling using AlphaMelts indicate that the melt segregations were generated after between 25 and 65% crystallization of a magma with the composition of the most primitive diabase, reaching up to 2,700 ppm H<sub>2</sub>O (0.27 wt%) in most evolved samples. The liquidus temperature was estimated at ca. 1170° C; most primitive melt segregation samples would be generated at ca. 1150°C and the most evolved at ca. 1090° C. Equilibration temperatures obtained from partitioning of rare-earth elements between clinopyroxene and plagioclase (Sun and Liang, 2017) are in agreement with the magma modeling data, and indicate  $\bar{x} = 1192 \pm 8$  °C for diabase and  $\bar{x} = 1081 \pm 18$ °C for melt segregations. AlphaMelts modeling indicates that density for the starting composition is 2.71 g/cm<sup>3</sup>, slightly raising to 2.72 g/cm<sup>2</sup> after 25%



crystallization and decreasing to 2.63 g/cm<sup>3</sup> after 65% crystallization in ideal crystal fractionation (fractionate100) model. Strongly incompatible elements such as Zr, Rb, Ba and Nb were shown to be the most reliable indicators of the crystallization/extraction rate.

In the course of this research, a wealth of additional data, mostly from electron microscopy and in situ major and trace-element chemistry of major mineral phases (pyroxene, plagioclase and olivine) were obtained. These will be used to further investigate the magma evolution of the CJS, and help identify and quantify the process of generation of gabbroic melt segregations.

### **3 – References**

- Ernesto, M., Raposo, M. I. B., Marques, L. S., Renne, P. R., Diogo, L. A., & De Min, A. (1999). Paleomagnetism, geochemistry and <sup>40</sup>Ar/<sup>39</sup>Ar dating of the North-eastern Paraná Magmatic Province: tectonic implications. *Journal of Geodynamics*, 28(4-5), 321-340.
- Faria, C., A. (2012). *Evolução magmática do Sill de Limeira*. Master dissertation, University of São Paulo, São Paulo, 106p.
- Gomes, A. S., Vasconcelos, P. M., Ubide, T., & Vasconcellos, E. M. G. (2022). Magmatic and hydrothermal evolution of mafic pegmatites and their host basalts, Paraná Large Igneous Province, Brazil. *Lithos*, 408, 106547.
- Lino, L. M., Cavallaro, F. D. A., Vlach, S. R. D. F., & Coelho, D. C. (2018). 2D magnetometric modeling of a basic-intermediate intrusion geometry: geophysical and geological approaches applied to the Limeira intrusion, Paraná Magmatic Province (SP, Brazil). *Brazilian Journal of Geology*, 48, 305-315.

- Lino, L., M., & Vlach, S., R., F. (2021). Textural and Geochemical Evidence for Multiple, Sheet-Like Magma Pulses in the Limeira Intrusion-Paraná Magmatic Province, Brazil. *Journal of Petrology*.
- Machado, F. B. (2005). Geologia e aspectos petrológicos das rochas intrusivas e efusivas mesozóicas de parte da borda leste da bacia do Paraná no estado de São Paulo. Master dissertation, Estadual São Paulo University, Rio Claro, 193p.
- Oliveira E.P. & Dantas E. (2008). Closed System differentiation in Mesozoic High-Ti Basic Sill of Limeira, São Paulo State: Implications for the origin of bimodal felsic-mafic volcanic rocks in the Paraná Igneous Province. In: *Simpósio de Vulcanismo e Ambientes Associados, 4.*, Foz do Iguaçu, SBG. Anais SBG, Foz do Iguaçu.
- Oliveira, A. V., Vasconcellos, E. M. G., Licht, O. A. B., & dos Santos, A. M. (2020). Petrografia e geoquímica de pegmatitos básicos da Província Ígnea do Paraná, no sudoeste do estado do Paraná. *Geologia USP. Série Científica*, 20(4), 79-101.
- Oliveira, E. P., Sato, L., Gomes, L. C. C., & Martins, G. (1998). Large scale magmatic banding in mesozoic basic sill of the Paraná basin, Campinas, São Paulo State, Brazil. *Boletim IG-USP. Série Científica*, 29, 220-220.