UNIVERSIDADE DE SÃO PAULO
INSTITUTO DE GEOCIÊNCIAS

"Geochemical characterization of the Equatorial Atlantic Magmatic Province and its correlation with other magmatic events related to the South Atlantic Opening"

ANTOMAT AVELINO DE MACEDO FILHO

Tese de apresentada ao Programa de Pós-Graduação em Geociências – Geoquímica e Geotectônica para obtenção do título de Doutor em Ciências.

Área de concentração: Geotectônica

Orientadora: Profª. Drª. Maria Helena Bezerra Maia de Hollanda

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Tese de Doutorado

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SÃO PAULO
2021

To my family.

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So many miles I've walked,
So many rivers I've crossed,
So many battles I've lost,
Make me who I am today,
And when tomorrow it comes,
There'll be a brand new sun,
This song is not over,
It's just begun...

(Stick Figure)

ABSTRACT

Macêdo Filho, A.A., 2021. Geochemical characterization of the Equatorial Atlantic Magmatic Province and its correlation with other magmatic events related to the South Atlantic Opening. [Ph.D. Dissertation], São Paulo, Institute of Geoscience, University of São Paulo.

This work aims to study tholeiitic magmatic events presently exposed in NE Brazil and related to the evolution of the Atlantic continental margin during the Mesozoic. This magmatism is also correlated to the break-up of the West Gondwana supercontinent and are represented by mafic dike swarms crosscutting the Precambrian Borborema Province and intrusions (sill complexes dominantly) hosted in the Paleozoic Parnaíba Basin. The mafic dikes in the Borborema Province were until the beginning of this research restricted to a 350 km-long EW Rio Ceará-Mirim Swarm. However, high-resolution airborne magnetic surveys carried out on the province have shown its continuation toward SW, extending for an extra >650 km, and making up a total of >1,000 km in length across the province. A second set of dikes herein studied are hosted in the northern Borborema Province, named as Canindé Dike Swarm, where they extend for 380 km on a WNW-trend. The sills are commonly referred as the Sardinha Formation and compose a wide multilayered sill complex on the eastern Paleozoic section of the Parnaíba Basin. The close spatial relationship, petrological signatures and previous Early Cretaceous ages support the hypothesis of both events belonging to one major intrusive magmatic province: the Equatorial Atlantic Magmatic Province (EQUAMP). The petrological approach developed over the Rio Ceará Mirim-Canindé dikes and Sardinha sills (petrography, mineral chemistry, whole-rock geochemistry, and Sr-Nd-Pb isotopes) enabled the discrimination of two major geochemical groups: (1) high-Ti tholeiites (HT; TiO_2 > 2.0 wt.%), rich incompatible elements with initial $^{87}Sr/^{86}Sr$ (~0.706) and $\varepsilon Nd_{(130)}$ (-3.0 av.), and moderately radiogenic $^{206}Pb/^{204}Pb_{(m)}$ ratios of ~18.3; The HT melts sometimes form evolved rocks such as trachyandesites and trachytes with lower TiO_2 (generally < 2.5 wt.%; MgO < 3 wt.%). (2) Low-Ti tholeiites composed by evolved basaltic andesites with MgO < 6 wt.% and less radiogenic Nd ($\varepsilon Nd_{(130)}$ -4.65 to -4.40). The HT tholeiites are prevalent in dikes and sills. However, the LT group is reported just on the Borborema Province. These magmas have different degrees of enrichments in large ion lithophiles and light rare-earth elements, coupled with depletion in high-field-strength elements (Nb-Ta) and isotopic (Sr-Nd-Pb) signatures compatible with enriched mantle sources (EM-like). Additionally, few sets of dikes and sills have geochemical signature akin to the Central Atlantic Magmatic Province (CAMP). They form subalkaline (to transitional) basalts and basaltic andesites with MgO > 6 wt.% and slightly more radiogenic Nd ($\varepsilon Nd_{(130)}$ -1.3 av.), as similarly observed in the low-Ti Prevalent CAMP group. Two restrict sites in the Parnaíba Basin present very radiogenic Nd ($\varepsilon Nd_{(130)}$ ~6.1-3.3) and trace element pattern analogous to High-Ti CAMP. The geochemical-isotopic modelling processed for EQUAMP magma groups suggest an EM composition, which may be explained by mixing of DMM (Depleted MORB Mantle) with SCLM (Sub-Continental Lithospheric Mantle)-derived melts, plus minor crustal assimilation or an involvement of OIB (Ocean Island Basalt)-EM or FOZO/HIMU (via mantle plumes) and lithospheric melts. A possible explanation for EM magmas in the EQUAMP would be the Tristan-Gough hotspot. These magmas could have flooded throughout Rio Ceará Mirim-Transminas dike swarms toward NE South America forming the widespread HT tholeiitic dikes and sill complexes. Finally, a classic petrological comparison based on diverse geochemical parameters, isotopic data, as well as a (semi-)automated analysis processed with Self-Organizing Maps finds strong similarity between EQUAMP magmas and contemporaneous other tholeiitic plumbing systems of the Paraná-Etendeka Magmatic Province (PEMP) such as Florianópolis, Ponta Grossa, Resende-Ilha Grande, Southern Espírito Santo, Transminas dike swarms and Bero Volcanic complex

(Angola). These aspects combined with the possible physical link between the Rio Ceará Mirim and Transminas (PEMP) swarm and Riacho do Cordeiro and Vitória-Colatina swarms (PEMP) indicate that both provinces share similar mantle sources and magmatic processes. Consequently, it can be assumed that EQUAMP and PEMP form together a continental scale tholeiitic event related to the early opening stage of the South Atlantic Ocean, therefore designed as one major single LIP of Lower Cretaceous age that should be collectively referred as the South Atlantic Magmatic Province (SAMP).

Keywords: Tholeiitic magmatism, Magmatic plumbing systems, EM component, West Gondwana breakup, Large Igneous Provinces.

RESUMO

Macêdo Filho, A.A., 2021. “Geochemical characterization of the Equatorial Atlantic Magmatic Province and its correlation with other magmatic events related to the South Atlantic Opening”. [Tese de Doutorado], São Paulo, Instituto de Geociências, Universidade de São Paulo.

Este trabalho teve como objetivo estudar os eventos magmáticos toleíticos atualmente expostos no Nordeste do Brasil e relacionados à evolução da margem continental Atlântica durante Mesozoico. Este magmatismo também está relacionado à fragmentação incial do supercontinente Gondwana Ocidental, sendo representado por enxames de diques máficos cortando os terrenos Pré-cambrianos da Província Borborema e intrusões (domiantemente complexos de soleiras) hospedadas nas camadas paleozócicas da Bacia do Parnaíba. Os diques máficos estavam até o início desta pesquisa restritos a um enxame de diques EW do magmatismo Rio Ceará-Mirim com cerca de 350 km de extensão. No entanto, levantamentos magnéticos aerogeofísicos de alta resolução realizados na Província de Borborema mostraram sua continuação SW, estendendo-se por mais de 650 km, e perfazendo um total de mais de 1.000 km em extensão. Um segundo conjunto de diques aqui estudado está localizado no norte da Província de Borborema, denominado como Enxame de Diques Canindé, onde se estendem por 380 km em uma orientação WNW. As soleiras são comumente referidas como Formação Sardinha e compõem um amplo complexo de intrusões de múltiplas camadas na seção leste da Bacia do Parnaíba. A próxima relação espacial, assinaturas petrológicas e as idades prévias do Cretáceo Inferior apoiam a hipótese de ambos os eventos pertencerem a uma importante província magmática intrusiva: a Província Magmática do Atlântico Equatorial (PMAE). A abordagem petrológica desenvolvida sobre os diques Rio Ceará Mirim-Canindé e soleiras Sardinha (petrografia, química mineral, geoquímica de rocha inteira e isótopos Sr-Nd-Pb) permitiu a discriminação de dois grandes grupos geoquímicos: (1) toleítos de alto-Ti (HT; TiO_2> 2,0% em peso) ricos em elementos incompatíveis com $^{87}Sr/^{86}Sr$ inicial (~0,706), εNd (-3,0 av.), e proporções moderadamente radiogênicas de $^{206}Pb/^{204}Pb$ (~18,3). Este grupo HT às vezes forma rochas evoluídas, como traquiandesitos e traquitos com TiO_2 geralmente < 2,5% em peso e MgO < 3% em peso. (2) Toleítos de baixo TiO_2 (LT; TiO_2< 2,0% em peso) compostos por andesitos basálticos evoluídos com MgO < 6% em peso e Nd menos radiogênico (εNd -4,65 a -4,40). Os HT são prevalentes em diques e soleiras. No entanto, o grupo LT é relatado apenas na Província de Borborema. Esses grupos têm diferentes graus de enriquecimento em maiores, traços litófilos e elementos terras raras leves, juntamente com empobrecimento em elementos de alta intensidade de campo (Nb-Ta) e assinaturas isotópicas (Sr-Nd-Pb) que são compatíveis com manto enriquecido (componente EM). Além disso, alguns conjuntos de diques e soleiras têm assinatura geoquímica semelhante à Província Magmática do Atlântico Central (PMAC). Eles formam basaltos subalcalinos (a transicionais) e andesitos basálticos com MgO > 6% em peso e Nd ligeiramente mais radiogênico (εNd -1,3 av.) que são semelhantes ao grupo de baixo TiO_2 chamado “Prevalent CAMP”. Dois locais restritos na Bacia do Parnaíba apresentam também amostras com Nd muito radiogênico (εNd ~ 6.1-3.3) e padrão de elementos traço análogo ao “High-Ti CAMP”. A modelagem geoquímica-isotópica processada para os grupos de magma da PMAE sugere uma composição EM, que pode ser explicada pela mistura de DMM (*Depleted MORB Mantle*) com fundidos derivados do SCLM (*Sub-Continental Lithospheric Mantle*), além de menor assimilação crustal ou um envolvimento de OIB(*Ocean Island Basalt*)-EM ou FOZO/HIMU (via plumas mantélicas) e fontes litosféricas. Uma possível explicação para magmas EMI na PMAE seria o ponto de quente de Tristão da Cunha-Gough. Esses magmas podem ter fluido ao longo dos enxames de diques Rio Ceará Mirim-Transminas em direção ao NE da América do Sul, onde formaram os complexos de intrusões toleíticas de alto TiO_2. Finalmente, uma comparação petrológica clássica baseada

em diversos parâmetros geoquímicos, dados isotópicos, bem como uma análise (semi)automatizada processada com Mapas Auto-Organizáveis indica forte similaridade entre magmas PMAE e outros sistemas intrusivos toleíticos contemporâneos da Província Magmática do Paraná-Etendeka (PMPE) como os enxames de diques de Florianópolis, Ponta Grossa, Resende-Ilha Grande, Sul do Espírito Santo, Transminas e complexo Vulcânico de Bero (Angola). Esses aspectos combinados com a possível ligação física entre os enxames do Rio Ceará Mirim e Transminas e os enxames de Riacho do Cordeiro e Vitória-Colatina (PMPE) indicam que ambas as províncias compartilham fontes de manto e processos magmáticos semelhantes. Consequentemente, pode-se presumir que PMAE e PMPE formam juntas um evento toleítico de escala continental relacionado ao estágio inicial de abertura do Oceano Atlântico Sul, portanto, compondo um uma única LIP do Cretáceo Inferior, que poderia ser coletivamente referida como Província Magmática do Atlântico Sul (PMAS).

Palavras-chave: Magmatismo toleítico, Sistemas de condutos magmáticos, Componente EM, Dispersão do Gondwana Oeste, Grandes províncias ígneas.

1. INTRODUCTION

1.1. Presentation

This dissertation meets the requirements to obtain the degree of Doctor of Philosophy in the Graduate Program in Geochemistry and Geotectonics of the Institute of Geosciences - University of São Paulo. This project focus on the study of mafic magmatic events exposed in the NE Brazil that were related to the evolution of the Atlantic continental margin during the Early Cretaceous, represented by giant dike swarms hosted in the Borborema Province (Rio Ceará-Mirim Magmatism), and a sill complexes intruding the Parnaíba Basin (Sardinha Magmatism). The very close spatial relationship between these plumbing systems styles together with the synchronous ages led Hollanda et al. (2019) to consider them as a part of a single Large Igneous Province (LIP): the Equatorial Atlantic Magmatic Province - EQUAMP. In order to test this hypothesis, this work studied EQUAMP components on a geochemical perspective, charged with carrying out a complete geochemical (major and trace element) and isotopic (Sr, Nd, Pb) characterization of the dike swarms and sills based on a comprehensive sampling to integrate their evolutionary histories and mantle source(s) into a model of a single LIP. The new data still allowed to establish correlations with the Early Cretaceous Paraná-Etendeka Province and outline an integrative geodynamic model for the tholeiitic magmatism linked to the early stage of Equatorial/South Atlantic Ocean born.

1.2. Rationale

The beginning of the 1990s brought with it the recognition of two magmatic events exposed in NE Brazil that were emplaced time-related to the breakup of the West Gondwana continent and the consequent opening of the Equatorial/South Atlantic Ocean in the Early Cretaceous. They were described as: (i) a mafic dike swarm named Rio Ceará-Mirim dike swarm (RCM) intrusive in Precambrian terranes of the Borborema Province (Bellieni et al., 1992; Matos, 1992; Oliveira, 1992), and (ii) sills (and subordinate dikes) grouped as Sardinha Formation in the Paleozoic sedimentary succession of the eastern side of the Parnaíba Basin (Bellieni et al., 1990; Fodor et al., 1990). Dikes and sills whether outcropping in the basement or within the basin, are prevalently described as high TiO_2 tholeiitic diabases.

Defined as a 350 km-long E-trending linear dike swarm (Archanjo et al., 2000; Hollanda et al., 2006; Ngonge et al., 2016a), the extension and geometry of the RCM was

recently re-examined after high-resolution airborne magnetic data of the Borborema Province available by the Brazilian Geological Survey (CPRM). These data allowed to show that the RCM drastically turns from EW towards a NE-SW direction at approximately 38ºW, which continuously propagates for, at least, 600-700 km more in length. The current total size of about 1,000 km characterizes the RCM as a giant, arcuate dike swarm in the sense of Ernst and Buchan (1997). Despite this relevance, no geological study was carried out on the NE-trending segment of the RCM yet.

The Sardinha sills, in turn, are exposed along the eastern side of the Parnaíba Basin, i.e. adjacent to the outcrop area of the NE-trending RCM. Although sills are mapped from north to south along the entire eastern side of the basin, the groundbreaking works have restricted the sampling to a small central area ignoring much of the geographic (and maybe geochemical) representativeness of this magmatism. Supported by resources of the oil-gas industry, some scientific papers were recently published dealing on the geochemical aspects of these eastern sills (Silva et al., 2017; Oliveira, et al., 2018; Heilbron et al., 2018; Miloski et al., 2019, 2020). Despite the merits, important sampling gaps persist, especially in southeastern areas.

1.3. Objectives

This work brings a significant database of geochemical (major oxides and trace elements) and Sr-Nd-Pb isotope data obtained from the aforementioned igneous rocks – i.e., the dikes composing the NE-trending branch of the RCM and the intrusions that represent the Sardinha Magmatism. The data obtained for the NE-trending RCM were integrated with existing data for the dikes that constitute the E-trending branch of the RCM (Ngonge et al., 2016a) to discuss the petrogenesis of the entire dike swarm. A subordinate intrusive system named Canindé dike swarm was additionally investigated in a similar approach.

The specific objectives were:

- To map the area of occurrence of the dikes in the Borborema Province and sill complexes of the Parnaíba Basin;
- To identify the mineral assemblage and textures of studied events;
- To understand the history of magma crystallization using of the crystal size distribution (CSD) technique combined with mineral chemistry in plagioclase and pyroxene;

- To define geochemical groups, recognize which mechanisms had operated during the magma evolution (fractional crystallization, and crustal assimilation), and also infer about the nature of mantle source(s) by using of geochemical (major and trace elements) and Sr-Nd-Pb isotope data;
- To compare the geochemical signatures of the EQUAMP with other plumbing systems of the Paraná-Etendeka Magmatic Province using classical petrological classifications and machine learning-based tecnic of Self-Organizing Maps (SOM).

1.4. Dissertation Structure

The PhD dissertation is organized into nine chapters. Current **Chapter 1** presents the topic and aims of this work. **Chapter 2** includes a literature review on LIPs and the fundamentals of the analytical methods applied in this investigation. **Chapter 3** presents the mapping of the entire RCM and other minor dike swarms and the sill province within the Parnaíba Basin based on airborne magnetic anomalies, satellite remote sensing data and field checking. **Chapter 4** presents the paper "Mineral chemistry and crystal size distributions of mafic dikes and sills on the eastern border of the Parnaíba Basin, NE Brazil" published in the *Journal of Volcanology and Geothermal Research* (Macêdo Filho et al., 2019). Chapters **5** and **6** deal with the geochemical and isotopic characterization of the sills and RCM (plus the Canindé subswarm), respectively. **Chapter 7** brings the results of the crystal size distribution (CSD) study via a combination of image analysis and mineral chemistry by electron microprobe (EPMA) applied to the NE-trending RCM and the comparison with results published for the Sardinha sills. **Chapter 8** includes the results of geochemical comparison among the EQUAMP and Paraná-Etendeka plumbing systems explored via SOM. Finally, **Chapter 9** summarizes the concluding remarks of this research.

9. SYNTHESIS AND CONCLUDING REMARKS

A petrogenetic and geodynamical model to the Mesozoic magmatism in NE Brazil is proposed based on geological mapping, crystal size distribution analysis, mineral chemistry, and geochemical-isotopic characteristics of sills and dikes. Additionally, the data-intensive comparison using a Self-Organizing Maps approach allowed to establish geochemical correlation between Early Cretaceous tholeiitic plumbing systems of the Equatorial Atlantic and Paraná-Etendeka provinces. Considering the results arising from the combined different methodologies, the main conclusions of this work are highlighted:

- Dike swarms in the Borborema Province show high parallelism with the adjacent Atlantic margin. These intrusions also develop abundantly where they have an orientation analogous to the ductile fabric of the Precambrian basement. Therefore, the new map resultant from this study reinforces the intimate relationship of dike swarm emplacement, Precambrian basement structure control, and South Atlantic rift tectonics with extensional axis NW-SE oriented in NE Brazil.
- In the Parnaíba Basin, NNW-SSE-oriented dikes odd with trend of other swarms in the Borborema Province. Rather, these NW-dikes should better address to the Central Atlantic Magmatic Province (CAMP). Since they point to the CAMP focal zone in the Central Atlantic area as other Juro-Triassic dikes around the Equatorial margins of South America and Africa.
- The mafic sill complexes hosted in the eastern side of the Parnaíba Basin make ca. 7.500 km^2, which means that over 90% of magmatic rocks are stored in the subsurface as indicated on geophysical maps (Mocitaiba et al., 2017). The sills also exhibit evidence of Mosquito (CAMP) magmatism, predominantly hosted in the NE border of the basin, and few occurrences in SE side, while the central-eastern portion presents a high frequency of the Sardinha (EQUAMP) event.
- The CSD method combined with mineral chemistry of plagioclase and (eventually) clinopyroxene were used to better understand the crystallization history of intrusions on the eastern side of the Parnaíba Basin and RCM dikes. In both environments, diabases are holocrystalline to hypocrystalline formed by plagioclase (bytownite-andesine), augite, pigeonite, Fe–Ti oxides and late alkali-feldspar (on hypocrystalline types).

- EQUAMP intrusions record simple crystallization histories combined with high nucleation density of microlites in the final stage of crystallization. Residence estimated time for the full crystallization of sills reached one and one-half years, whereas for dikes in the Borborema Province two and a half years, suggesting that exposed sections of dikes are deeper intrusions than Parnaíba Basin sills.
- In the SE border of the Parnaíba Basin, where RCM dikes intercept the basal Silurian sequence, Sardinha sills and RCM dikes are apart from each other by 5 km. In that region, whole-rock geochemical-isotopic compositions, mineral chemistry, magnetic susceptibility, textural aspects, geochronological data and crystal size distribution patterns are basically the same. Therefore, the RCM dikes may have been the feeder system of sills complexes.
- In a possible model, the area covered by the Parnaíba Basin at the Early Cretaceous could have been much larger than present-day boundaries, and the dikes could be the remnants of a complex system feeding sills on the sedimentary layer above at the Mesozoic. Additionally, the hypothesis of feeder dikes beneath the basin must not be ruled out, since the RCM and Canindé swarms tend to form a diffuse arrangement from the Borborema Province towards the Parnaíba Basin, where dikes give way to sill complexes.
- The sampling achieved in this work allowed to greatly expand the knowledge about magmatic events in the eastern side of the Parnaíba Basin. Elementary geochemistry and radiogenic isotopes were applied to classify geochemical groups and as a first-order screening tool to segment different magmatic events, since two LIPs share the same geographic area in the basin.
- The new data showed the predominance of HT tholeiites (HT1; TiO_2 >2 wt.%; MgO < ~6 wt.%) enriched in incompatible elements which are reported on the central-southeastern areas with major oxides, trace elements and isotopic characteristics (εNd -2.1 to -3.0) and moderately radiogenic $^{206}Pb/^{204}Pb$ ratios (~18.25) analogous to the reported values of the HT Sardinha magmatism.
- On a few sites, such as Elesbão Veloso, HT tholeiites coexist with trachyandesites to trachytes wich show the same isotopic characteristics; therefore, they were interpreted as a fractionated product from HT melts. The Sardinha magmatism has been age constrained at the Early Cretaceous (e.g., Baksi and Archibald, 1997; Heilbron et al., 2018; Fernandes et al., 2020) and, therefore, addressed to the EQUAMP event.

- A second more important group concern to LT tholeiites (TiO_2 < 2 wt.%; MgO > 5 wt.%), poor in incompatible elements and reported on the NE border of the basin, with subordinate occurrences in the central and southern sections of the basin. LT showed geochemical-isotopically (εNd -0.98 to -1.71) signatures akin to the Prevalent low-Ti CAMP (Marzoli et al., 2018), age constrained around at ~201 Ma by the $^{39}Ar/^{40}Ar$ method (e.g., Merle et al., 2011; Heilbron et al., 2018; Fernandes et al., 2020; Davies et al., 2017).
- An additional geochemical group of HT tholeiites (HT2), presenting more primitive characteristics (εNd 6.1-3.3), were correlated to high-Ti CAMP basalts. Consequently, the paradigm in segmenting LIP influence areas as Mosquito event/CAMP in the western side, and Sardinha event/EQUAMP on the eastern side must be reviewed, since both LIPs coexist in the eastern section of the Parnaíba Basin.
- The RCM and Canindé dikes showed HT (TiO_2 > 2.0 wt.%) compositions, associated with evolved HT (trachyandesites and trachytes). These diabases present εNd between -2.90 to -2.56, and moderately radiogenic $^{206}Pb/^{204}Pb$ ratios (~18.3). The geochemical-isotopic signature of HT RCM resembles those of the Sardinha Sills in the Parnaíba Basin. These results, in conjunction with geochronological data available in the literature, support a single LIP event, confirming the hypothesis of Hollanda et al. (2019).
- Two groups of low-Ti tholeiites (TiO_2 < 2 wt.%) were characterized in the RCM swarm, an evolved group (LT1) presenting MgO < 6 wt.% and less radiogenic Nd (εNd -4.6 to -4.4), and another more magnesian (LT2, MgO >6 wt.%) with slightly more radiogenic Nd (εNd -1.4 to -1.0).
- In the regional context, HT melts of the EQUAMP have similar composition of contemporaneous HT magma types of the PEMP, whereas LT tholeiites have geochemical signatures analogous to CAMP and or PEMP low-Ti magmas (e.g., Esmeralda type). A K-Ar approach led by Oliveira et al. (2021) outlined an Early Cretaceous age to the evolved LT magmas (LT1), these results did not preclude the possibility of a CAMP provinciality to more magnesian tholeiites (LT2).
- The geochemical data of both HT and LT tholeiites require the involvement of variable proportions of an enriched component that can be either the subcontinental metasomatized mantle itself (case of LT) or a deep plume (case of HT). By assuming

the involvement of a plume, Ascension-St. Helena and Tristan-Gough are likely candidates. Crustal contamination must have occurred to some extent.

- If a FOZO-type (Ascension) plume is involved, the role of the SCLM is required as a 'subordinate' component with proportions not greater than 30%. The SCLM is not (or negligibly) needed if an EM-Gough plume was involved.
- A plausive hypothesis to justify the presence of HT Gough-type next to the Equatorial Atlantic would be the physical link between the NE-RCM and the Transminas dike swarms, which have the same geochemical-isotopic signature and suggestive lateral continuity in aeromagnetic maps. Therefore, magmas would be generated in the Tristan-Gough plume, and subsequently migrate to NE Brazil via this up to 2,300 km-long plumbing system. A similar link between EQUAMP and PEMP is outlined by Vitória-Colatina and Riacho do Cordeiro dikes swarms, totalizing at least 1,600 km-long, which present comparable geochemical-isotopic compositions and age.
- Even if the EM-Gough hotspot is considered as the source of HT magmas, few compositions reported in EW-RCM and Benue Rift still require the involvement of FOZO/HIMU components. It might suggest that northern (Ascencion-St. Helena) and southern (Tristan-Gough) hotspots played a role in the tectonomagmatic activity of South Atlantic rifting.
- The revaluation of the geochemical database of the PEMP and the EQUAMP, through classical petrological approach as well as through Self-Organizing Maps, indicates that the compositional diversity of EQUAMP rocks is completely encompassed in the PEMP compositional range. These relationships are even clearer for the HT group, which has a lower degree of crustal contamination than LT magmas, as suggested by isotopic data and patterns of trace elements.
- In conclusion, the EQUAMP integrate the framework of Lower Cretaceous LIPs in the West Gondwana realm, in addition to Paraná and Etendeka provinces, where they form one major single LIP ($> 9.5 \times 10^6$ km²) related to the early stage of South Atlantic Rift. Rather, these igneous manifestations should be collectively referred as the South Atlantic Magmatic Province (SAMP). Such model simplifies the genesis of the Atlantic Ocean with three major magmatic provinces: Central Atlantic (CAMP; Juro-Triassic), South Atlantic (SAMP; Early Cretaceous) and North Atlantic (NAMP; Paleogene).

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