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GEOTECTÔNICA)**

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**CHANGES IN HYDROCLIMATE AND VEGETATION IN THE SÃO FRANCISCO
RIVER DRAINAGE BASIN DURING THE LAST 45000 YEARS**

São Paulo
2021

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Versão resumida

Dissertação apresentada ao Programa de Pós-Graduação em Geociências (Geoquímica e Geotectônica) do Instituto de Geociências da Universidade de São Paulo como requisito para obtenção do título de Mestre em Ciências

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Orientador:
Prof. Dr. Cristiano Mazur Chiessi

São Paulo
2021

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**Changes in hydroclimate and vegetation in the São Francisco River drainage basin
during the last 45000 years**

JAQUELINE QUIRINO FERREIRA

Orientador: Prof. Dr. Cristiano Mazur Chiessi

Dissertação de Mestrado

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ABSTRACT

Ferreira, J.Q, **Changes in hydroclimate and vegetation in the São Francisco River Drainage Basin during the last 45000 years.** [Master's Thesis], São Paulo, Instituto de Geociências, Universidade de São Paulo, 2021. 60 pp.

The São Francisco River Drainage Basin is the larger hydrographic system in eastern South America. This basin has a huge ecological importance due to its extension and because it hosts a large portion of Cerrado (a type of tropical savanna), as well as Caatinga and, subordinately, Atlantic Forest. Despite that, the main factors that controlled changes in the biomes during the last tens of thousands of years and were, at least partially, responsible for their current distribution are still largely unknown. This is due to the small number of long paleoenvironmental reconstructions that integrate large areas of the São Francisco River basin. Here, we used the stable hydrogen (δD) and carbon ($\delta^{13}\text{C}$) isotope composition of long-chain *n*-alkanes from a marine sediment core to reconstruct past hydroclimate and vegetation, respectively, in an independent way. Long-chain *n*-alkanes are plant-wax biomarkers present in the wax coating of leaves. δD values of plant-waxes register the isotope composition of meteoric water, which is, in turn, controlled by the amount effect in the tropics. Hence, the δD of plant-waxes can be used to reconstruct past precipitation. $\delta^{13}\text{C}$ values of plant-waxes allows the differentiation between vegetation types using the C3 and C4 photosynthetic pathways. Since tropical forest taxa mostly use the C3 metabolisms, while tropical savanna taxa predominantly use the C4 metabolism, this method allows to study potential shifts in the dominant vegetation type. To do so, we analyzed marine sediment core M125-95-3 collected from the western tropical South Atlantic (10.94°S, 36.20°W, 1897 m water depth, 1040 cm core length), near the mouth of the São Francisco River, spanning the last 45 kyr. On top of millennial-scale changes, $\delta^{13}\text{C}$ data indicate for the first time a marked obliquity control over the proportion of trees (C3) versus grasses (C4). During periods of maximum (minimum) obliquity, trees (grasses) reached maximum coverage. Importantly, our δD record does not indicate orbital-scale changes in precipitation. We suggest that maximum (minimum) obliquity decreased (increased) the length of the dry season allowing (hampering) the development of trees. Periods of maximum (minimum) obliquity increased (decreased) the intra-hemispheric insolation gradient during austral winter, strengthening the austral Hadley circulation and the southeastern trade winds. Both processes slightly increased winter precipitation over the São Francisco River Drainage Basin, decreasing the length of the dry

season. Our results suggest that the dry season length is a governing factor in the long-term control of tree density in tropical savannas.

Keywords: Quaternary; South America; vegetation; orbital forcing; long chain *n*-alkanes.

RESUMO

Ferreira, J.Q, **Mudanças no hidroclima e vegetação na Bacia do Rio São Francisco durante os últimos 45000 anos.** [Dissertação de Mestrado], São Paulo, Instituto de Geociências, Universidade de São Paulo, 2021. 60 pp.

A bacia hidrográfica do rio São Francisco é o maior sistema hidrográfico do leste da América do Sul. Esta bacia possui grande importância ecológica devido à sua extensão e por abrigar parte substancial do Cerrado (um tipo de savana tropical), além de amplas áreas de Caatinga e, subordinadamente, Mata Atlântica. Apesar disso, os principais fatores que controlaram as alterações nestes biomas durante as últimas dezenas de milhares de anos e foram, pelo menos em parte, responsáveis pela sua atual distribuição, são ainda amplamente desconhecidos. Isto se deve ao pequeno número de reconstituições paleoambientais longas que integrem extensas áreas da bacia do rio São Francisco. Neste estudo a composição dos isótopos estáveis de hidrogênio (δD) e carbono ($\delta^{13}C$) de *n*-alcanos de cadeia longa de um testemunho sedimentar marinho foi usada para reconstituir a história geológica do hidroclima e da vegetação da bacia, respectivamente, de forma independente. *n*-Alcanos de cadeia longa são biomarcadores vegetais presentes no revestimento de cera das folhas. Os valores de δD de ceras vegetais refletem a composição isotópica da água meteórica, que é controlada pelo “*amount effect*” nos trópicos. Dessa forma, δD de ceras vegetais pode ser usado para reconstituir a precipitação pretérita. Já os valores de $\delta^{13}C$ de ceras vegetais permitem diferenciar os tipos de vegetação usando as vias fotossintéticas C3 e C4. Uma vez que táxons de floresta tropical usam principalmente o metabolismo C3, enquanto que os táxons de savana tropical usam principalmente o metabolismo C4, este método permite reconstituir mudanças potenciais no tipo de vegetação dominante. Para isso, analisamos o testemunho sedimentar marinho M125-95-3 coletado na porção oeste do Atlântico Sul tropical (10,94°S, 36,20°W, lâmina d'água de 1897 m, 1040 cm de comprimento), próximo à foz do rio São Francisco, abrangendo os últimos 45 kyr. Em adição às mudanças milenares, os dados de $\delta^{13}C$ mostram pela primeira vez o controle da obliquidade sobre a proporção de árvores (C3) versus gramíneas (C4). Durante os períodos de obliquidade máxima (mínima), as árvores (gramíneas) atingiram a maior cobertura. O registro de δD , entretanto, não indica mudanças na precipitação na escala orbital. Sugere-se que a obliquidade máxima (mínima) diminuiu (aumentou) a duração da estação seca, permitindo (dificultando) a expansão da cobertura de árvores. Períodos de obliquidade máxima (mínima) aumentaram (diminuíram) o gradiente de insolação intra-

hemisférico durante o inverno austral, fortalecendo a circulação de Hadley do hemisfério sul e os ventos alísios de sudeste. Ambos processos aumentaram ligeiramente a precipitação de inverno austral na bacia do rio São Francisco, diminuindo a duração da estação seca. Nossos resultados sugerem que a duração da estação seca é um fator determinante no controle de longo prazo da densidade de árvores em savanas tropicais.

Palavras-chave: Quaternário; América do Sul; vegetação; forçante orbital; *n*-alcanos de cadeia longa.

TABLE OF CONTENTS

1 CHAPTER 1	14
1.1 INTRODUCTION	14
1.2 RESEARCH AIMS	18
2 CHAPTER 2	19
2.1 LONG CHAIN <i>n</i> -ALKANES	19
2.2 PALEOENVIRONMENTAL RECONSTRUCTIONS IN EASTERN SOUTH AMERICA.....	25
3 CHAPTER 3	31
4 CHAPTER 4	32
4.1 CONCLUSIONS	32
REFERENCES	33

LIST OF FIGURES

Figure 1.1 Precipitation charts for selected stations in the São Francisco São Francisco River Drainage Basin (note the different y-axis values). A. Fazenda Coqueiro (São Desidério/BA). B. Lagoa das Pedras (Montalvânia/MG). C. Barra do Escuro (São Romão/MG). D. IBO (Abaré/BA). E. Pão de Açúcar (Pão de Açúcar/AL). F. Jaguaruna – jusante (Onça de Pitangui/MG). Data obtained from Agência Nacional de Águas (ANA)	14
Figure 1.2 Distribution of biomes in eastern South America (IBGE, 2004). The location of marine sediment core M125-95-3 is indicated by a green circle	16
Figure 2.1 Histogram showing normal distribution of bulk C3 and C4 plant isotopic values (Tippie & Pagani, 2007)	21
Figure 2.2 Box plots of $\delta^{13}\text{C}$ data from soil bulk organic matter available for the São Francisco River Drainage Basin and its direct neighborhood (Mendonça et al., 2010; Pessenda et al., 1996, 1998; 2010). The data for Cerrado and Forest are indicated by the green and orange box plots, respectively.....	22
Figure 2.3 Relationships between source-water δD and lipid biomarker δD values from lake-surface sediment samples from Europe, Africa and the Americas (Sachse et al., 2012)	24
Figure 2.4 Long term means (monthly) and associated standard deviation of δD (rainwater) obtained from Global Network of Isotopes in Precipitation database. Accessible at: https://nucleus.iaea.org/wiser . Data from Belo Horizonte (blue line and dot), Brasília (orange line and square) and Floresta (red line and triangle) stations.....	24
Figure 2.5 Location of selected palynological records (pink circles) from the São Francisco River Drainage Basin and its direct neighborhood, on top of the distribution of Brazilian biomes (IBGE, 2004). 1. São José palm swamp (Cassino et al., 2018) 2. Icatu River Valley (De Oliveira et al., 1999a) 3. Lagoa Feia (Cassino et al., 2020) 4. Chapadão dos Gerais	

(Franco Cassino & Meyer, 2013) **5.** Pinheiro mire (Horák-Terra et al., 2020) **6.** Lagoa Nova (Behling, 2003) **7.** Salitre de Minas (Ledru, 1993). The location of the M125-95-3 marine core is indicated by the green circle in **8**.....28

Figure 2.6 Eastern South American paleoenvironmental records over the last ca. 35 kyr. **A.** Speleothems stable oxygen isotopic record ($\delta^{18}\text{O}$) from eastern Brazil (Stríkis et al., 2018). **B.** $\ln(\text{Ti}/\text{Ca})$ data of core M125-95-3 (Campos et al., 2019). **C.** $\delta^{13}\text{C}$ from peat core Pinheiro mire (Horák-Terra et al., 2020). **D.** Obliquity values (Laskar et al., 2004). **E.** Arboreal pollen percentage (AP %) from Lagoa Feia (Cassino et al., 2020). **F.** AP% from Pinheiro mire (Horák-Terra et al., 2020). See Table 2.1 and Figure 2.5 for the location of the described records30

LIST OF TABLES

Table 2.1 Selected palynological records from the São Francisco River Drainage Basin and its direct neighborhood. For the location of the records see Figure 2.5	29
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1 CHAPTER 1

1.1 INTRODUCTION

The São Francisco River Drainage Basin (SFRB) is the larger river system in eastern South America. Starting in the Serra da Canastra at ca. 20°S (southeastern Brazil), the São Francisco River flows northwards until ca. 10°S, when it veers eastwards reaching the tropical South Atlantic around 10.5°S (Figure 1.1). The headlands of the SFRB are under the influence of the South Atlantic Convergence Zone (SACZ), a NW-SE oriented convective belt originating in the Amazon Basin that extends over southeastern South America and over the adjacent South Atlantic (Carvalho et al., 2004). The SACZ is a distinctive feature of the South American Monsoon System (SAMS), that dominates the seasonal precipitation cycle in South America (Vera et al., 2006; Zhou & Lau, 1998), which has its mature phase in austral summer (December-February) (Vera et al., 2006). Due to this influence, the headlands of the SFRB are wetter than the rest of the basin (Figure 1.1).

Figure 1.1 Precipitation charts for selected stations in the São Francisco River Drainage Basin (note the different y-axis values). **A.** Fazenda Coqueiro (São Desidério/BA, 1973 - 2018). **B.** Lagoa das Pedras (Montalvânia/MG, 1969-2018). **C.** Barra do Escuro (São Romão/MG, 1956-2018). **D.** IBO (Abaré/BA, 1969-2018). **E.** Pão de Açúcar (Pão de Açúcar/AL, 1935-2018). **F.** Jaguaruna – jusante (Onça de Pitangui/MG, 1942-2018). Data obtained from Agência Nacional de Águas (ANA).

The SAMS intensity is dominantly influenced by changes in austral summer insolation, that in turn is strongly associated with the precession cycle (period of ca. 23 ka) (Cheng et al., 2013; Cruz et al., 2005; Govin et al., 2014; Hou et al., 2020). In the upper-

troposphere, the convective activity associated to the SAMS produces the Bolivian High over the Altiplano that is dynamically linked to the Nordeste Low over northeastern Brazil (Lenters & Cook, 1997). The Nordeste Low, in turn, produces large-scale subsidence over northeastern Brazil that affects the northern portion of the SFRB. In a precession-driven high austral summer insolation situation a strengthened SAMS intensifies this circulation pattern, increasing precipitation over the western Amazon and under the SACZ, as well aridity over northeastern Brazil (Cheng et al., 2013; Cruz et al., 2009).

Because of the opposing hydroclimatic influences over the southern and northern realms of the SFRB, speleothem-based precipitation records from the central portion of the SFRB show no clear precession-driven changes (Stríkis et al., 2018). These records, along with other studies (Campos et al., 2019; Stríkis et al., 2011), indicate that precipitation over this portion of eastern South America was strongly modulated by millennial-scale events. Based on data from marine sediment core M125-95-3 collected off the mouth of the SFRB, Campos et al. (2019) corroborated the lack of orbital-scale changes in hydroclimate and proposed that positive precipitation anomalies over the SFRB during the so-called Heinrich Stadials (HS) (Bond et al., 1992; Heinrich, 1988; Sanchez Goñi & Harrison, 2010) were associated with increased austral summer rainfall over eastern tropical South America. According to this mechanism, increased austral summer rainfall occurred due to an anomalous cyclonic circulation and moisture transport from the warmer South Atlantic into the continent.

The central SFRB hosts a large portion of Cerrado biome (Figure 1.2), a complex ecosystem with mixed trees and grasses, ranging from tree-less open vegetation (Campo Limpo) with a dense grassland ground, to a closed canopy with a dense occurrence of trees (Cerradão) and associated gallery forests following the watercourses (Bridgewater et al., 2004; Da Silva & Bates, 2002; Toby Pennington et al., 2000). The northern portion of the SFRB is covered by Caatinga formations (Figure 1.2) - a type of tropical dry forest, composed by xerophytic, woody, thorny and deciduous physiognomies (Sampaio, 1995). Atlantic Forest occurs over the southern portion of the SFRB and along a narrow coastal stripe close to the coast of northeastern Brazil (Figure 1.2) and is composed by two major vegetation types: the Atlantic Rain Forest, which runs along the coastline, and the Atlantic Semi-deciduous Forest, which occupies higher elevation inland areas (Oliveira-Filho & Fontes, 2000).

Figure 1.2 Distribution of biomes in eastern South America (IBGE, 2004). The location of marine sediment core M125-95-3 is indicated by the green circle.

Accurate reconstructions of hydroclimate and vegetational changes in this area are critical to understanding the potential influence of climate variability over tropical biogeography and biodiversity (Bouimetarhan et al., 2018; Dupont et al., 2010). Despite important efforts undertaken to reconstruct past dynamics of the Cerrado (Cassino et al., 2020; Cassino & Meyer, 2013; Horák-Terra et al., 2020), Caatinga (De Oliveira et al., 1999) and Tropical forest (Behling, 2003), available records are either short or have a localized

meaning. Paleoenvironmental information from a marine sediment core integrating large portions of the SFRB, for instance, is largely missing.

Plant biomarkers have been recognized as an important tool to reconstruct past climatic and vegetational changes (Huang, 2001; Schefuß et al., 2011). Changes in environmental conditions are imprinted on the molecular residues of organisms that lived during different past times. Thus, the composition of compounds like lipids present in sediments record paleoenvironmental changes (Meyers, 1997). *n*-Alkanes are commonly used as paleoenvironmental signal carriers since they record past environmental conditions and present excellent preservation against degradation during transport and deposition (Diefendorf & Freimuth, 2017; Häggi et al., 2017).

Marine sediment core M125-95-3 (Bahr et al., 2016) collected off the SFRB mouth, was investigated within this Master's dissertation (Figure 1.2). The core covers the last ca. 45 kyr (Campos et al., 2019). We used the stable carbon ($\delta^{13}\text{C}$) and hydrogen (δD) isotopic composition of epicuticular waxes (i.e., long-chain *n*-alkanes) of terrestrial higher plants to reconstruct the main photosynthetic pathway of vegetation (i.e., C3 trees versus C4 grasses) and the amount of precipitation, respectively, over the SFRB. The performed analytical results, together with their interpretation, constitute a manuscript (Chapter 3) entitled "*Changes in obliquity drive biome shifts in eastern tropical South America*" (under submission). In this manuscript, we show evidence and describe how the dry season length is a governing factor in the long-term control of tree density in tropical savannas of the SFRB area.

In this dissertation, a review of *n*-alkanes and available paleoenvironmental records of interest to this study is provided in Chapter 2. A full description of the material and methods used in this study can be found in the manuscript (Chapter 3), together with the regional setting of the SFRB. Final conclusions are presented in Chapter 4.

1.2 RESEARCH AIMS

This Master's dissertation aims to contribute to the understating of the hydroclimate and vegetational dynamics in the SFRB (i.e, eastern South America) for the last ca. 45 kyr. To reach this aim, the following activities were performed:

1. Reconstruction of past changes in precipitation over the SFRB based in the δD of long-chain *n*-alkanes;
2. Reconstruction of past changes in the predominant photosynthetic pathway of SFRB vegetation based in the $\delta^{13}C$ of long-chain *n*-alkanes;
3. Reconstruction of the climatic mechanisms responsible for the inferred paleoenvironmental variations;
4. Comparison and contextualization of the obtained data with records available in the literature.

2 CHAPTER 2

2.1 LONG CHAIN *n*-ALKANES

Long-chain *n*-alkanes and other organic compounds, such as *n*-alkanoic acids, *n*-alkanols and *n*-esters, constitute the epicuticular wax, which act as a protective layer in terrestrial plants (Eglinton & Hamilton, 1967). *n*-Alkanes correspond to the group of saturated aliphatic hydrocarbons, represented by the formula C_nH_{2n+2} . Their C-C and C-H covalent bonds are exceedingly difficult to break, so these molecules tend to be preserved over geological time. These lipid biomarkers can be produced by algae, bacteria, terrestrial plants and be derived from degradation of petrogenetic processes. They are available in the form of fossils in soils and sediments from lakes, rivers and marine environments (Sachse, et al., 2012; Schefuß et al., 2003; Smith & Freeman, 2006).

The chain length can indicate the source of these compounds. Long-chain *n*-alkanes (C_{21} - C_{35}) produced by vascular terrestrial plants have a predominance of odd numbered chain, since they are compounds formed from enzymatic conversion by decarboxylation. *n*-Alkanes produced by aquatic algae and aquatic plants produce shorter chains (C_{17} - C_{21}) (Bush & McInerney, 2013; Castañeda & Schouten, 2011).

Since plants adapt to different degrees of water availability, the increase in the chain length provides a higher efficiency in retaining water, hindering evapotranspiration. Smaller odd chains (C_{17}) are characteristic of material of marine origin, such as macroalgae, phytoplankton and phanerogams (Meyers, 2003). Medium chains (C_{21} - C_{25}) are characteristic of marine macrophytes, while long chain compounds (C_{27} - C_{35}) are characteristic of terrestrial vascular plants (Bush & McInerney, 2013; Castañeda & Schouten, 2011).

Several methods have been applied to characterize the distribution of *n*-alkanes. The Carbon Preference Index (CPI) (equation 2.1) provides information about the predominance of odd over even carbon number molecular chains. Values of $CPI > 1$ indicate a predominance of odd chains in the sample, pointing to a possible plant source, while $CPI < 1$ indicates that the source of the material is of petrogenic origin, or even anthropic (Eglinton & Hamilton, 1967).

$$CPI_{27-33} = 0.5 * \left(\frac{nC_{27} + nC_{29} + nC_{31} + nC_{33}}{nC_{26} + nC_{28} + nC_{30} + nC_{32}} + \frac{nC_{27} + nC_{29} + nC_{31} + nC_{33}}{nC_{28} + nC_{30} + nC_{32} + nC_{34}} \right)$$

(2.1)

Carbon fixation in photosynthesis can occur through three metabolic pathways: C3 (Calvin-Benson), C4 (Hatch-Slack) or CAM (crassulacean acid metabolism) (Bianchi & Canuel, 2011). The type of metabolism used by plants also influences the size of *n*-alkane chains. C4 plants tend to have higher concentrations of longer chain *n*-alkanes (C₃₁, C₃₃, C₃₅) than C3 plants (Garcin et al., 2014). The Average Chain Length (ACL) index (equation 2.2) is thus used to differentiate the size of the chains in *n*-alkanes.

$$ACL_{27-33} = \frac{27 * nC_{27} + 29 * nC_{29} + 31 * nC_{31} + 33 * nC_{33}}{nC_{27} + nC_{29} + nC_{31} + nC_{33}}$$

(2.2)

During photosynthesis, plants strongly fractionate carbon isotopes. Different carbon-fixing pathways produce *n*-alkanes with different carbon isotopic signatures. The C3 photosynthetic pathway presents the largest net fractionation, whereas the C4 pathway the smallest one (Diefendorf & Freimuth, 2017; O’Leary, 1988). The stable carbon isotopic composition ($\delta^{13}\text{C}$) of long-chain *n*-alkanes can be used to distinguish between plants that use the C3 (average *n*-alkane $\delta^{13}\text{C}$ of -34.7‰ for the C₂₉) or C4 photosynthetic pathways (average *n*-alkane $\delta^{13}\text{C}$ of -21.4‰ for the C₂₉) (Castañeda & Schouten, 2011).

Figure 2.1 illustrates the differences in $\delta^{13}\text{C}$ for plants using different photosynthetic metabolisms. Generally, soil bulk $\delta^{13}\text{C}$ values are more enriched than long-chain *n*-alkanes. The difference varies from biome to biome, but a study performed in South America indicates a difference of ca. 6‰ (Wu et al., 2019).

Figure 2.1 Histogram showing normal distribution of bulk C₃ and C₄ plant isotopic values (Tippie & Pagani, 2007).

C₃ plants (trees, shrubs and cool-climate grasses) dominate Tropical forest and savannas with a closed canopy, while C₄ plants (tropical grasses) dominate open savannas (Garcin et al., 2014; Lloyd et al., 2008). Thus, the analysis of long-chain *n*-alkanes $\delta^{13}\text{C}$ can provide the composition (C₃ versus C₄) of vegetation in tropical regions and the dominant biome (Häggi et al., 2016; Schefuß et al., 2005). Importantly, biomes do not exclusively feature C₃ or C₄ vegetation. Usually, they have a mix of C₃ and C₄ plants, as is the case of Cerrado (Toby Pennington et al., 2000).

In the absence of $\delta^{13}\text{C}$ values for modern long-chain *n*-alkanes from the different biomes of the SFRB, we compiled the $\delta^{13}\text{C}$ values available in the literature from soil bulk organic matter covering savanna (Cerrado) and forest ecosystems from the SFRB and its direct neighborhood (Figure 2.2). The compiled data confirm the more enriched $\delta^{13}\text{C}$ signal of Cerrado (median -25.4 ‰) compared to the forest signal (median -26.9 ‰).

Figure 2.2 Box plots of $\delta^{13}\text{C}$ data from soil bulk organic matter available for the São Francisco River Drainage Basin and its direct neighborhood (Mendonça et al., 2010; Pessenda et al., 1996, 1998; 2010). The data for Cerrado and Forest are indicated by the orange and green box plots, respectively.

The δD of long chain *n*-alkanes indicate the environmental conditions during the formation of the epicuticular waxes. Since water is the primary source of hydrogen for photosynthetic organisms, organic hydrogen in lipids preserved in sediments deposited offshore can provide information about continental hydroclimate of a given region (Collins et al., 2017; Schefuß et al., 2005, 2011).

During sea water evaporation ($\delta D = 0\text{‰}$), the corresponding vapor will be depleted in the heavier isotope D, since $^1\text{H}_2^{16}\text{O}$ has a higher vapor pressure than $^1\text{D}^{16}\text{O}$. After condensation, the resulting rain is enriched in D compared to the vapor (Sachse et al., 2012).

Dansgaard (1964) identified some factors that control the δD values in precipitation: (i) “continental effect” will occur as air masses lose moisture over the continent, where the preferential loss of D results in lower δD values as air masses move further inland; (ii) “temperature effect” occurs in regions with intense temperature variability; and (iii) “amount effect”, which occurs in tropical regions, where the rainfall regime is strongly marked by seasonality and, the depletion in D is related to higher precipitation rates.

The δD of long-chain *n*-alkanes reflect the isotopic composition of the water used by the producing organism (Schefuß et al., 2005) (Figure 2.3). The δD values of lipid biomarkers are offset from, but highly correlated with, the water source used by these organisms (Sachse et al., 2012). Current δD data from rainwater at SFRB stations were extracted from the Global Network of Isotopes in Precipitation (GNIP) database (Figure 2.4). δD values from the station closest to the headlands (Belo Horizonte) are more depleted than those near the northernmost station of the SFRB (Floresta), which is closest to the mouth of the river. The data confirm that within the SFRB, regions with higher amount of rainfall (Figure 1.1) show more negative δD values.

Figure 2.3 Relationships between source-water δD and lipid biomarker δD values from lake-surface sediment samples from Europe, Africa and the Americas (Sachse et al., 2012).

Figure 2.4. Long term means (monthly) and associated standard deviation of rainwater δD from three different stations located in direct neighborhood of the São Francisco River Drainage Basin (Global Network of Isotopes in Precipitation database, accessible at <https://nucleus.iaea.org/wiser>). Data from Belo Horizonte/MG (blue line and dot), Brasília/DF (orange line and square) and Floresta/PE (red line and triangle) stations.

Due to the accumulation of the lighter hydrogen isotope (^1H) in continental ice sheets during the last glacial, the mean isotopic composition of hydrogen in the rest of the global hydrological cycle became more D-enriched (by 8‰ on average) compared to present day conditions. This ice volume effect must be accounted for when reconstructing past environmental conditions by applying an ice volume correction (IVC) as the one described in equation 2.3 (Tierney and deMenocal, 2013).

$$\delta\text{D}_{\text{wax-IVC}} = \frac{1000 + \delta\text{D}_{\text{wax}}}{8 \cdot 0.001 \cdot \delta^{18}\text{O}_{\text{isoice}} + 1} - 1000 \quad (2.3)$$

Where $\delta\text{D}_{\text{wax-IVC}}$ represents the ice volume corrected isotope values, $\delta\text{D}_{\text{wax}}$ the measured δD of plant-waxes and $\delta^{18}\text{O}_{\text{isoice}}$ the effect of ice volume on the benthic $\delta^{18}\text{O}$ variation (Bintanja et al., 2005).

2.2 PALEOENVIRONMENTAL RECONSTRUCTIONS IN EASTERN SOUTH AMERICA

The SFRB is the largest hydrographic system in eastern South America. Accurate reconstructions of past vegetation in this area are critical to understand the dynamics of Neotropical biogeography and biodiversity. Despite this, the main factors that control biomes changes during the last tens of thousands of years and, at least in part, were responsible for their current distribution are still largely unknown. This is due to the small number of long paleoenvironmental reconstructions that integrate large areas of the São Francisco river basin.

Marine sedimentary records can greatly contribute to understanding past changes in continental vegetation (Häggi et al., 2017; Mulitza et al., 2017). Data from northern NE Brazil, for instance, indicated wet conditions during the YD interval that were accompanied by the expansion of Tropical forest (Bouimetarhan et al., 2018; Mulitza et al., 2017). Vegetation over northern NE Brazil also showed a response to increased precipitation during HS1, the landscape once dominated by grasses and shrubs showed an expansion in forest phytophysionomies (Behling et al., 2000; Dupont et al., 2010; Jennerjahn et al., 2004; Mulitza et al., 2017).

These records greatly contributed to understanding the past dynamics of vegetation over northern NE Brazil. However, they are located under the influence of the Intertropical

Convergence Zone (ITCZ), a global convective belt over the oceans associated to the ascending branch of the Hadley cell and to the convergence of the NE and SE trade winds (Marshall, 2014; Schneider et al., 2014). The ITCZ annual mean latitudinal position is around 5°N and, despite its southward displacements during HS events (Mulitza et al., 2017; Portillo-Ramos et al., 2017; Mendes et al., 2019; Venancio et al., 2020; Zhang et al., 2017), it is unlikely to have influenced the SFRB. Indeed, the northernmost portion of the SFRB is located at ca. 8°S and does not show a typical yearly precipitation distribution for a site influenced by the southernmost position of the ITCZ (i.e., peak in precipitation during March-May) (Figure 1.1) (Garreaud et al., 2009; Hastenrath, 2012; Schneider et al., 2014).

Investigating marine sediment core M125-95-3 (Figure 1.2) (the same core investigated in this dissertation), Campos et al. (2019) suggested positive excursions in precipitation to have occurred over the SFRB during HS and the YD. The mechanism proposed to explain the positive excursions goes beyond changes in SAMS. According to Campos et al. (2019), eastern South America was affected by an anomalous tropical South Atlantic cyclonic circulation during HS and the YD. The SFRB was affected by increased precipitation mainly during the extended austral summer. In the continent, speleothem records (Stríkis et al., 2018) indeed indicate increases in precipitation during HS and the YD. Importantly, neither the marine sediment core nor the speleothems show orbital signals, neither precession nor obliquity.

Several palynological studies have been carried out based on paleoenvironmental archives collected within or in the direct neighborhood of the SFRB (Table 2.1; Figure 2.5). Horák-Terra et al. (2020) suggest the occurrence of a long dry season from ca. 35-25 ka BP in the eastern edge of the basin (Figure 2.5), with a reduction in arboreal pollen (AP) (Figure 2.6f) and the highest $\delta^{13}\text{C}$ values (Figure 2.6c), indicating a higher contribution of C4 plants during this period than in any other from this record. Cassino et al. (2020) indicate the occurrence of an open landscape in central Cerrado (Figure 2.5) at ca. 19-13 ka BP followed by a forest/arboreal savanna expansion between ca. 12.5 and 11.2 ka BP (Figure 2.6e). Humid conditions associated with the expansion of trees and a short dry season were indicated for Chapadão dos Gerais (Figure 2.5) (Cassino & Meyer, 2013) between ca. 13.5 and 11.6 ka BP, and for Salitre de Minas (Figure 2.5) (Ledru, 1993) between ca. 13 and 11 ka BP. Northern Cerrado data (Cassino et al., 2018) also indicate an increase in AP during the Pleistocene-Holocene transition (ca. 14.6, 13.4, 12.2 and 11 ka BP samples). During the early Holocene, the southern portion of the SFRB showed an open landscape with small areas of gallery forests along the drainage systems (Behling, 2003), associated with a moisture decline

(Cassino et al., 2020). On the other hand, in the northern portion of the SFRB (currently dominated by Caatinga, Figure 2.5) the early Holocene was characterized by the presence of a dense forest cover with a high frequency of tree elements from the Atlantic Forest (De Oliveira et al., 1999).

Despite the detailed descriptions about variations of the phytophysionomies, none of these studies cover one complete obliquity period (ca. 41 ka) (Table 2.1), which could facilitate the identification of a possible obliquity influence on vegetation. In addition, the different hydroclimate controls active over distinct portions of the SFRB (Figure 1.1) make any specific continental paleoenvironmental record unable to register the basin-integrated vegetational dynamics. Indeed, past variations in austral summer insolation, for instance, resulted in opposite hydroclimate changes in the southern versus the northern portions of the SFRB (Prado et al., 2013; Prado et al., 2013b). Thus, only a paleoenvironmental archive that to some extent integrates a larger portion of the SFRB would be able to record orbital-scale changes in the vegetation of the basin.

Figure 2.5 Location of selected palynological records (pink circles) from the São Francisco River Drainage Basin and its direct neighborhood, on top of the distribution of Brazilian biomes (IBGE, 2004). **1.** São José palm swamp (Cassino et al., 2018) **2.** Icatu River Valley (De Oliveira et al., 1999a) **3.** Lagoa Feia (Cassino et al., 2020) **4.** Chapadão dos Gerais (Franco Cassino & Meyer, 2013) **5.** Pinheiro mire (Horák-Terra et al., 2020) **6.** Lagoa Nova (Behling, 2003) **7.** Salitre de Minas (Ledru, 1993). The location of the M125-95-3 marine core is indicated by the green circle in **8**.

Table 2.1 Selected palynological records from the São Francisco River Drainage Basin and its direct neighborhood. For the location of the records see Figure 2.5.

Location	Number of the record in Figure 2.5	Type of record	Interval covered by the record (ka BP)	Reference
Pinheiro Mire	5	Peat core	35-0	Horák-Terra et al. (2020)
Lagoa Feia	3	Lake core	19-4.5	Cassino et al. (2020)
São José palm swamp	1	Peat core	15.7-0	Cassino et al. (2018)
Icatu river valley	2	Peat core	10.9-4.2	Oliveira et al. (1999)
Salitre de Minas	7	Peat core	32-3.1	Ledru (1993)
Lagoa Nova	6	Lake core	10.2-0.2	Behling (2003)
Vereda Laçador	4	Palm swamp	13.3-1.3	Cassino & Meyer (2013)

Figure 2.6 Eastern South American paleoenvironmental records over the last ca. 35 kyr. **A.** Speleothems stable oxygen isotopic record ($\delta^{18}\text{O}$) from eastern Brazil (Stríkis et al., 2018). **B.** $\ln(\text{Ti}/\text{Ca})$ data of core M125-95-3 (Campos et al., 2019). **C.** $\delta^{13}\text{C}$ from peat core Pinheiro mire (Horák-Terra et al., 2020). **D.** Obliquity values (Laskar et al., 2004). **E.** Arboreal pollen percentage (AP %) from Lagoa Feia (Cassino et al., 2020). **F.** AP% from Pinheiro mire (Horák-Terra et al., 2020). See Table 2.1 and Figure 2.5 for the location of the described records.

3 CHAPTER 3**Changes in obliquity drive biome shifts in eastern tropical South America**

4 CHAPTER 4

4.1 CONCLUSIONS

The investigation of the long-chain *n*-alkanes from a marine sediment core collected off the mouth of the São Francisco River allowed a better understanding of the major hydrological and vegetational changes that occurred in the SFRB during the last ca. 45 kyr. From this, our main conclusions are:

- I. The δD and $\delta^{13}C$ composition of plant-wax *n*-alkanes are useful tools for the reconstruction of the amount of precipitation and the dominant vegetation type (i.e., C3 versus C4), respectively, in the SFRB.
- II. Despite the strong control that precession exerts over the strength of the SAMS, neither our δD_{wax} nor our $\delta^{13}C_{wax}$ records show this type of orbital pacing.
- III. Our δD_{wax} data show no orbital pacing at all.
- IV. Our δD_{wax} record indicates increases in precipitation over the SFRB during HS4-HS1. For the first time, a basin-integrated signal from a direct precipitation indicator is provided.
- V. Our $\delta^{13}C_{wax}$ record shows a prominent obliquity pacing. For the first time, we show that obliquity influences vegetation dynamics in eastern tropical South America through its control of the DSL. We suggest that periods of maximum (minimum) obliquity increased (decreased) the intra-hemispheric insolation gradient during austral winter, strengthening the austral Hadley circulation and the southeastern trade winds. These processes slightly increased winter precipitation over the São Francisco river drainage basin, decreasing the length of the dry season.
- VI. Our $\delta^{13}C_{wax}$ record also shows variability in response to millennial-scale climate change events. Different HS show a distinct response depending on the obliquity phase. HS4 and HS1 occurred during high obliquity when DSL was short, which led to a C3 spread over the basin. HS3 and HS2, on the other hand, occurred during low obliquity, when DSL was long, which led to C4 spread over the basin.

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