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INSTITUTE OF GEOSCIENCES

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Modern terrigenous sediment sources and past changes in precipitation over tropical South America recorded in terrigenous sediments deposited in the western equatorial Atlantic

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Dissertação de Mestrado

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RESUMO

Grigolato Iani, J., 2023. **Modern terrigenous sediment sources and past changes in precipitation over tropical South America recorded in terrigenous sediments deposited in the western equatorial Atlantic** (Master's dissertation). São Paulo, Institute of Geosciences, University of São Paulo, 2023.

O efeito da desaceleração da Célula de Revolvimento Meridional do Atlântico (CRMA) sobre a precipitação na Bacia Amazônica é uma questão crucial para o futuro da floresta Amazônica. No final do Quaternário, a CRMA foi significativamente reduzida durante os *Heinrich Stadials* (HS). Esses períodos de diminuição da CRMA em escala milenar oferecem uma oportunidade valiosa para examinar e avaliar o impacto da intensidade da CRMA na precipitação Amazônica. Apesar do esforço investido durante a última década na compreensão dos efeitos dos HS sobre a Bacia Amazônica, a resposta deste sistema fluvial transcontinental às mudanças na intensidade da CRMA durante o HS mais recente (i.e., HS0 ou *Younger Dryas*, 12,9 – 11,7 cal ka BP) permanece incerta. Esta dissertação de mestrado teve como principal objetivo caracterizar como as mudanças na intensidade da CRMA afetaram a precipitação Amazônica durante os últimos 28.000 anos. Para atingir tal objetivo, em uma primeira etapa, elementos maiores em sedimentos suspensos dos rios Negro, Solimões e Amazonas foram analisados por espectrometria de emissão óptica com plasma indutivamente acoplado (ICP-OES, na sigla em Inglês) em amostras que cobrem um ciclo hidrológico anual completo, de modo a avaliar a dinâmica fluvial atual da Bacia Amazônica. Esses dados forneceram uma base sólida para a segunda etapa da dissertação, a saber a reconstituição paleoclimática da Bacia Amazônica, realizada com ênfase no *Heinrich Stadial 1* (HS1) (18,6 – 14,7 cal ka BP) e no *Younger Dryas*. A reconstituição paleoclimática baseou-se em dois testemunhos sedimentares marinhos coletados no Atlântico equatorial ocidental, datados por radiocarbono, analisados por fluorescência de raios-X por energia dispersiva (ED-XRF, na sigla em Inglês) e interpretados com auxílio de análise de componentes principais. A interpretação dos dados produzidos para o *Younger Dryas* foi também auxiliada por uma compilação de registros hidroclimáticos da Bacia Amazônica e arredores, bem como com uma saída da rodada transiente TraCE-21ka do modelo numérico climático CCSM3. Os resultados obtidos mostram que o HS1 teve duas fases distintas: o HS1a entre 18,6 e 16,7 cal ka BP e o HS1b entre 16,7 e 14,7 cal ka BP. O HS1a é caracterizado por altos valores de ln(Ti/Ca) e de ln(Ti/Al) e baixos valores de ln(Al/K) e ln(Fe/K), enquanto que o HS1b é caracterizado por valores relativamente mais baixos de ln(Ti/Ca) e ln(Ti/Al) e relativamente mais altos de ln(Al/K) e ln(Fe/K). As diferenças entre HS1a e HS1b estão relacionadas a uma mudança no locus principal de precipitação: os Andes centrais durante o HS1a e as terras baixas do sudeste da Bacia Amazônica durante o HS1b. A mudança no locus principal de precipitação sobre a Bacia Amazônica foi provavelmente determinado por uma diminuição acentuada na intensidade da CRMA durante o HS1b, quando a mesma atingiu sua menor intensidade durante a última deglaciação. Os resultados para o *Younger Dryas* sugerem respostas distintas da precipitação sobre a Bacia Amazônica. Enquanto seu início é marcado pelo aumento de ln(Ti/Ca) e ln(Al/K) além da diminuição de ln(Fe/K) e ln(Ti/Al), o restante do evento apresenta valores menores de ln(Ti/Ca) e ln(Ti/Al) e valores maiores de ln(Al/K) e ln(Fe/K). Sugere-se que a diminuição da insolação de verão austral que caracteriza o período entre o HS1 e o *Younger Dryas* enfraqueceu o Sistema de Monções da América do Sul e a Zona de Convergência Intertropical tornou-se, gradativamente, a principal fonte de umidade para a Bacia Amazônica. Estas feições atmosféricas influenciam a precipitação amazônica de maneira distinta. As diferentes respostas da precipitação Amazônica durante o HS1 e o *Younger Dryas* estão, portanto, relacionadas à desaceleração da CRMA e à variação da insolação de verão austral. A variada resposta da precipitação em cada evento e sub-evento reforça a importância dos estudos paleoclimáticos na Bacia Amazônica e a necessidade de compartimentalizar a mesma em função da sua alta complexidade e dimensão continental.

Palavras-chave: Célula de Revolvimento Meridional do Atlântico, Heinrich Stadials, Bacia Amazônica, Younger Dryas.

ABSTRACT

Grigolato Iani, J., 2023. **Modern terrigenous sediment sources and past changes in precipitation over tropical South America recorded in terrigenous sediments deposited in the western equatorial Atlantic** (Master's dissertation). São Paulo, Institute of Geosciences, University of São Paulo, 2023.

The effect of the slowdown of the Atlantic Meridional Overturning Circulation (AMOC) on precipitation in the Amazon Basin is a crucial issue for the future of the Amazon rainforest. At the end of the Quaternary, the AMOC strength was significantly reduced during the Heinrich Stadials (HS). These millennial-scale periods of AMOC decline offer a valuable opportunity to examine and assess the impact of AMOC intensity on Amazonian precipitation. Despite the efforts made during the last decade to understand the effects of HS on the Amazon Basin, the response of this transcontinental river system to changes in AMOC strength during the most recent HS (i.e., HS0 or Younger Dryas, 12.9 – 11.7 cal ka BP) remains uncertain. This master's dissertation aimed at characterizing how changes in AMOC strength affected Amazonian precipitation during the last 28,000 years. To achieve this objective, in a first step, major elements in suspended sediments from the Negro, Solimões and Amazonas Rivers were analyzed by inductively coupled plasma optical emission spectrometry (ICP-OES) covering a complete annual hydrological cycle, in order to evaluate the current fluvial dynamics of the Amazon Basin. These data provide a solid basis for the second stage of the dissertation, namely the paleoclimatic reconstruction of the Amazon Basin, carried out with emphasis on the Heinrich Stadial 1 (HS1) (18.6 – 14.7 cal ka BP) and the Younger Dryas. The paleoclimate reconstruction was based on two marine sediment cores collected from the western equatorial Atlantic, radiocarbon dated, analyzed by energy dispersive X-ray fluorescence (ED-XRF) and interpreted with the aid of principal component analysis. Interpretation of the data produced for the Younger Dryas was also aided by a compilation of hydroclimatic records from the Amazon Basin and its surroundings, as well as outputs from the transient TraCE-21ka run of the numerical climate model CCSM3. The results show that HS1 had two distinct phases: HS1a between 18.6 and 16.7 cal ka BP and HS1b between 16.7 and 14.7 cal ka BP. HS1a is characterized by high values of ln(Ti/Ca) and ln(Ti/Al), and low values of ln(Al/K) and ln(Fe/K), whereas HS1b is characterized by relatively lower values of ln(Ti/Ca) and ln(Ti/Al), and relatively higher of ln(Al/K) and ln(Fe/K). The differences between HS1a and HS1b are related to a shift in the main locus of precipitation: the central Andes during HS1a and the southeastern lowlands of the Amazon Basin during HS1b. The change in the main locus of precipitation over the Amazon Basin was likely driven by a marked decrease in AMOC strength during HS1b, that reached its lowest level during the last deglaciation. Results for the Younger Dryas suggest distinct precipitation responses over the Amazon Basin. While its beginning is marked by an increase in ln(Ti/Ca) and ln(Al/K) and a decrease in ln(Fe/K) and ln(Ti/Al), the remainder of the event presents lower values of ln(Ti/Ca) and ln(Ti/Al) and higher values of ln(Al/K) and ln(Fe/K). We suggest that the decrease in austral summer insolation that characterized the period between HS1 and the Younger Dryas weakened the South American Monsoon System, and the Intertropical Convergence Zone gradually became the main source of moisture for the Amazon Basin. These atmospheric features influence precipitation over the Amazon Basin in distinct ways. The different responses of Amazonian precipitation during HS1 and the Younger Dryas are, therefore, related to the slowdown of the AMOC and changes in austral summer insolation. The variation in precipitation response in each event and sub-event reinforces the importance of paleoclimate studies in the Amazon Basin and the need to compartmentalize it in terms of its high complexity and continental dimension.

Keywords: Atlantic Meridional Overturning Circulation, Heinrich Stadials, Amazon Basin, Younger Dryas.

1 INTRODUCTION

The Amazon Basin, in South America, is the largest drainage basin in the world. Spanning 6 × 10^6 km^2, it holds the title for the most extensive drainage area on the planet, with an average annual water discharge of 200,000 m^3 s^{-1} and average annual suspended sediment discharge of 1,100 × 10^6 to 1,300 × 10^6 t into the equatorial Atlantic (Meade, 1994). The Amazon River and its tributaries drain many different geological terrains, ranging from pre-Cambrian rocks in the northern and southern shields (Guianas and Brazilian Shields, respectively) to Cenozoic rocks of the Andean orogenic system in the west to Cenozoic sediments in the lowlands (Stallard and Edmond, 1983; Gómez et al., 2019) (Figure 1).

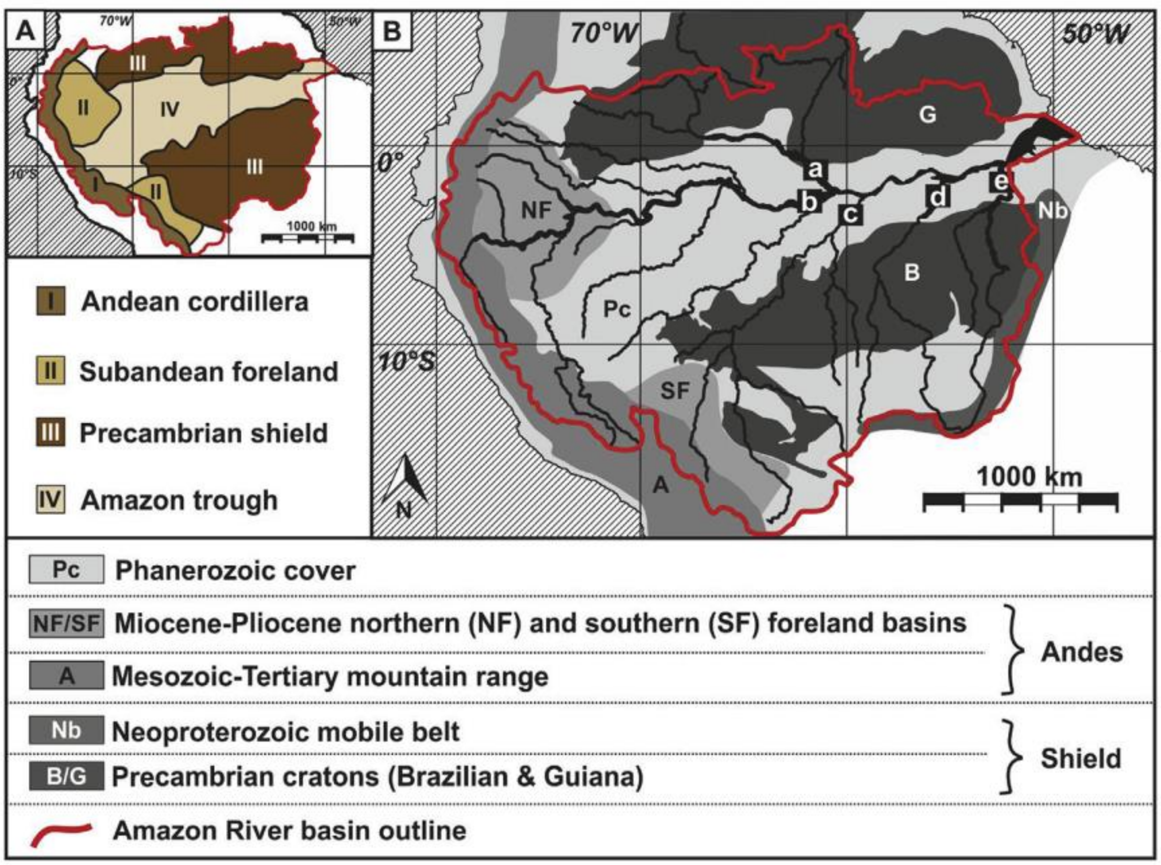

Figure 1. Main geological features of the Amazon Basin. (A) Morphostructural zones of the Amazon Basin (Stallard and Edmond, 1993). (B) Geological units over the Amazon Basin and its main rivers (a) Negro River, (b) Solimões River, (c) Madeira River, (d) Tapajós River and (e) Xingu River. The red outline is the boundary of the Amazon Basin (Extracted from (Höppner et al., 2018).

The Amazon Basin is under the influence of two main atmospheric systems: the South America Monsoon System (SAMS) and the Intertropical Convergence Zone (ITCZ) (Kang et al., 2008; Donohoe et al., 2013). The SAMS is a crucial component responsible for supplying moisture to the Amazon Basin (> 2,000 mm yr^{-1}) (Vera et al., 2006; Liebmann and Mechoso, 2011). It serves as the primary mechanism for delivering water vapor and precipitation to the region. This atmospheric feature develops in response to seasonal variations in the thermal contrast between South America and the South Atlantic (Vera et al., 2006), resulting in a seasonal shift in atmospheric circulation pattern (when the average mean annual circulation is subtracted), bringing in moist air from the tropical Atlantic Ocean towards the Amazon Basin. The ITCZ represents a key characteristic of the ascending branch of the Hadley cell system (Donohoe et al., 2013) and its position is intrinsically tied to the meridional gradient in sea surface temperature (Philander et al., 1996). During the boreal summer, a period characterized by the North Atlantic receiving maximum solar radiation (insolation), the ITCZ undergoes a northward shift, migrating to approximately 10°N. During the austral summer, the ITCZ migrates southward, to approximately 1°S latitude (Nobre and Shukla, 1996). The position of the ITCZ is influenced by various factors, including sea surface temperatures, solar radiation, and atmospheric dynamics. One of the key factors influencing the ITCZ position, on the scale of thousands of years, is the Atlantic Meridional Overturning Circulation (AMOC) (Zhang and Delworth, 2005; Broccoli et al., 2006; Marshall et al., 2014). The AMOC is a large-scale oceanic circulation pattern in the Atlantic Ocean, transporting heat and freshwater (Kuhlbrodt et al., 2007). This oceanic circulation is caused by the movement of surface warm and saline waters from the tropics towards the North Atlantic, where they cool, become denser, and sink to deeper layers, returning deep cold waters to the South Atlantic. The ITCZ and AMOC interact through ocean-atmosphere feedback. Weakening of the AMOC alter the meridional SST gradient, changing atmospheric circulation patterns and, therefore, the position of the ITCZ. Weakening of the AMOC over the 21st century, causing abrupt shifts in SAMS and ITCZ, is a key topic of the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2022).

To better understand the possible outcomes of a weakened future AMOC a number of studies addressed the influence that a weakened AMOC had in the ocean-atmospheric system in the past (e.g., Portilho-Ramos et al., 2017; Zhang et al., 2017; Campos et al., 2019; Crivellari et al., 2019;

Pinho et al., 2021) The AMOC weakened several times in the past, especially during Heinrich Stadials (HS) (Boyle and Keigwin, 1987; Oppo and Lehman, 1995; Curry et al., 1999). This happened due to the inflow of fresh water in the high latitudes of the North Atlantic, which caused anomalies in the formation of North Atlantic Deep Water (the water mass that for the deep southward flowing branch of the AMOC). Although studies have identified correlations between variations in the intensity of the AMOC and past abrupt changes in the SAMS and ITCZ, our understanding about the ocean-atmosphere interplay during the most recent AMOC weakening event (namely Heinrich Stadial 0, also known as the Younger Dryas) is still limited. Moreover, understanding the response of the Amazon Basin to recent SAMS and ITCZ anomalies is fundamental to future climate projections, as the Amazon rainforest is often regarded as a climate tipping element (McKay et al., 2022).

In this dissertation, we assessed how variations in AMOC strength affected precipitation over the Amazon Basin during Heinrich Stadial 1 and the Younger Dryas. Therefore, we first improved our understanding about the modern suspended sediment dynamics in the Amazon Basin and then reconstructed the changes in terrigenous sediment discharge by the Amazon River to the western equatorial Atlantic during the last 28 thousand years (ka).

2 CONCLUSIONS

The HS1 was marked by increased terrigenous input to the site of composite core GGC4_CDH5, due to increased erosion and precipitation over the Amazon Basin. Variations in major elements allowed the subdivision of HS1 into two phases. The HS1a, ranging from 18.6 to 16.7 cal ka BP, is characterized by higher ln(Ti/Ca) and ln(Ti/Al), lower values of ln(Fe/K) and lower values of ln(Al/K), suggesting increased precipitation over the Andes. High austral summer insolation combined with weak AMOC during HS1a led to an intensification of the SAMS and a southward migration of the ITCZ, causing higher precipitation in the Central Andes. HS1b, from 16.7 to 14.7 cal ka BP, is characterized by a very weak AMOC, when the ITCZ was displaced even further south, shifting the main locus of precipitation from the central Andes to the lowlands. During the YD, ln(Ti/Ca) is biased due to sea level rise and continental shelf flooding, hindering its use as a precipitation proxy. PC1, which is mainly controlled by Si and Al, increases during YD, likely indicating increased precipitation in the Amazon Basin. Importantly, elemental ratios from composite core GGC4-CDH5 behave differently during HS1 and the YD, with an increase in ln(Al/K) and decrease in ln(Fe/K) and ln(Ti/Al) during the YD. Modern ln(Fe/Al) data from Amazonian suspended sediments shows that increased discharge from the Amazon River during the austral winter causes an increase in ln(Fe/Al) and is related to higher precipitation during austral summer. The compilation of hydroclimatic records for the YD combined with the TraCE-21ka output shows increased precipitation during the YD over the western, southern and eastern Amazon Basin, as well as over northeastern Brazil. Taken together, we suggest last two Heinrich Stadials (HS1 and HS0, or the YD) were not homogeneous, mainly due to the differences in AMOC intensity and austral summer insolation. The differences between Heinrich Stadials reinforce the importance of paleoclimate studies in understanding possible future consequences of a weakening AMOC. The Amazon Basin has continental dimensions and telecommunicates with other regions in South America and beyond. Therefore, appropriately projecting changes in the precipitation main locus is a task of utmost important.

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