Universidade de Brasília

Intituto de Geociências

Programa de Pós-Graduação em Geociências Aplicadas e Geodinâmica

Dissertação n°: 181

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Paula Ribeiro Bianchini

Master's Dissertation

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Master's Dissertation

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Abstract

Changes in the global energy budget have effects on moisture fluxes, with impacts on precipitation regimes. During the Holocene (last ~12,000 years), the orbital forcing altered the insolation on the top of the atmosphere, influencing seasonality and global temperatures. Monsoon systems are a very important component of tropical precipitation and respond to the differential heating of the continents and oceans along the year. In the American continent, the North American Monsoon System (NAMS) and the South American Monsoon System (SAMS) can be interpreted as two axes of the same cycle and their combination characterizes the American Monsoon System (AMS). In Central Brazil, the SAMS generates intense rainfall during austral summer, but changes in global climate may impact on its position and magnitude. Lake sediments constitute an important archive for reconstructing long-term fluctuations in environmental conditions, mainly changes in precipitation regimes. In the present study, lake sediments were used to understand how the AMS has varied during the Holocene. A compilation of paleoclimatic and paleoenvironmental studies in lake sediments showed that the choice and use of each proxy requires prior assessment, considering the entire environmental context, and the pros and cons associated with each proxy. It was possible to identify that it is important to study as many proxies as possible (multiproxy approach) for a broader view of its context than could be acquired from a single proxy, and that accurate dating is essential in paleoclimatic studies. A reliable age model with calibrated ages is also essential as the degree of success in discerning patterns of climate and environmental change depends on the level of correlation of paleorecords, which is related to the quality of the age model. A compilation of paleoclimatic and paleoenvironmental studies based on lake sediments in the region of influence of the AMS show that the NAMS was weakening and the SAMS was gaining strength throughout the Holocene, with these changes occurring due to the increase in insolation in the Southern Hemisphere, with a consequent decrease in insolation in the Northern Hemisphere and a displacement of the Intertropical Convergence Zone to the south. A reanalysis of Lagoa Feia sediments in Central Brazil showed climate variability during the Holocene, with an alternation between the drier and wetter periods. A relatively wetter period at Lagoa Feia was identified during the dry Mid-Holocene, around 5000 years. These results promote a better understanding of how the American monsoon has varied during the past 12000 years, with consequences in Central Brazil.

Keywords: **Lacustrine sediment, multiproxy, calibration, Holocene, NAMS, SAMS, Lagoa Feia.**

Resumo

Mudanças no balanço global de energia têm efeitos nos fluxos de umidade, com impactos nos regimes de precipitação. Durante o Holoceno (últimos ~ 12.000 anos), a forçante orbital alterou a insolação no topo da atmosfera, influenciando a sazonalidade e as temperaturas globais. Os sistemas de monções são um componente muito importante da precipitação tropical e respondem ao aquecimento diferencial dos continentes e oceanos ao longo do ano. No continente americano, o Sistema de Monção Norte Americano (SMNA) e o Sistema de Monção Sul Americano (SMSA) podem ser interpretados como dois eixos de um mesmo ciclo, e sua combinação caracteriza o Sistema de Monção Americano (SMA). No Brasil Central, o SMSA gera chuvas intensas durante o verão austral, mas mudanças no clima global podem impactar em sua posição e magnitude. Os sedimentos de lago constituem um importante arquivo para reconstruir flutuações de longo prazo nas condições ambientais, principalmente mudanças nos regimes de precipitação. No presente estudo, sedimentos de lagos foram usados para entender como o SMA variou durante o Holoceno. Uma compilação de estudos paleoclimáticos e paleoambientais em sedimentos lacustres mostrou que a escolha e o uso de cada proxy requerem uma avaliação prévia, considerando todo o contexto ambiental e os prós e contras associados a cada proxy. Foi possível identificar que é importante estudar o maior número de proxies possível (abordagem multiproxy) para uma visão mais ampla de seu contexto do que poderia ser adquirido de um único proxy, e que datações precisas são essenciais em estudos paleoclimáticos. Um modelo de idade confiável com idades calibradas também é essencial, pois o grau de sucesso em discernir padrões de mudança climática e ambiental depende do nível de correlação dos paleorregistros, que está relacionado à qualidade do modelo de idade. Uma compilação de estudos paleoclimáticos e paleoambientais baseados em sedimentos lacustres na região de influência do SMA mostra que o SMNA foi enfraquencendo e o SMSA foi ganhando força ao longo do Holoceno, tendo essas mudanças ocorrido pelo aumento de insolação no Hemisfério Sul, com consequente diminuição de insolação no Hemisfério Norte e deslocamento da Zona de Convergência Intertropical para sul. Uma reanálise dos sedimentos da Lagoa Feia no Brasil Central mostrou variabilidade climática durante o Holoceno, com uma alternância entre os períodos mais secos e mais úmidos. Um período relativamente mais úmido na Lagoa Feia foi identificado durante o Holoceno Médio seco, por volta de 5000 anos. Esses resultados promovem um melhor entendimento de como as monções americanas têm variado nos últimos 12.000 anos, com consequências no Brasil Central.

Palavras-chave: **Sedimento lacustre, multiproxy, calibração, Holoceno, SMNA, SMSA, Lagoa Feia.**

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Chapter 1

Introduction

Climatic variations have driven the biological and social evolution of the human species for many years, since they have contributed to the rise and collapse of civilization throughout human history, as they influence the ability of humans to produce agricultural products at the levels necessary to sustain them (Brevik et al., 2018; Gowdy, 2020). Climate change and its impacts on soils and civilizations are a major topic of interest today, as studying what happened in the past during these changes can help us understand what is likely to happen in the future. Study how people in the past adapted or not to these changes can provide us with an insight into potential success or failure strategies to adapt to future climate change (Brevik et al., 2018). The understanding of climatic variability has become essential to our knowledge of the ancient civilization since the unique climate stability of the Holocene made agriculture possible once the climate instability of earlier epochs made it impossible (Feynman and Ruzmaikin, 2018). Therefore, from the first plantations to the present, successful agriculture depends on an understanding of climatic behavior. Asian and European peoples have been studying the behavior of the climate and its influence on agriculture for millennia. Similarly, American pre-Columbian peoples have also developed knowledge about the climate and its impacts on agriculture. The Wari people, for example, created innovative and highly efficient agricultural systems to guarantee their survival during periods of aridity, such as between 600 and 700 A.D. (Denevan, 2001; Winterhalder et al., 1994). Knowledge about the climate of South America, specially the moonson activity, is currently important for agriculture, as this continent is an important agricultural producer in the world (USDA, 2019).

Monsoons are a dominant feature of the tropical and subtropical climate in many regions of the world characterized by rainy summer and drier winter seasons and accompanied by a seasonal reversal of the prevailing winds (Geen et al., 2020). These systems occur in response to seasonal changes in the thermal contrast between the continent and the adjacent oceanic regions (Vera et al., 2006). In the American continent there is the formation of classical anticyclones of the monsoon system at higher levels, with an intense flow of moisture from the ocean to the continent at lower levels (Mechoso et al., 2004). The monsoon system present in this region is called the American Monsoon System (AMS), which is composed of the North America Monsoon System (NAMS) and the South American Monsoon System (SAMS) (Figure 1). Both systems receive more than 50% of the total annual precipitation during the respective summer monsoons, although the precipitation values of SAMS are a little higher (Figueroa and Nobre, 1990; Higgins et al., 1997; Vera et al., 2006). In South America (SA), SAMS's operations are more expressive, characterized by intense rainfall over central Brazil, with rains concentrated in the southern summer months, in a region that is connected to the Intertropical Convergence Zone (ZCIT) of the Atlantic to the northeast (Mechoso et al., 2004; Silva and Kousky, 2012).

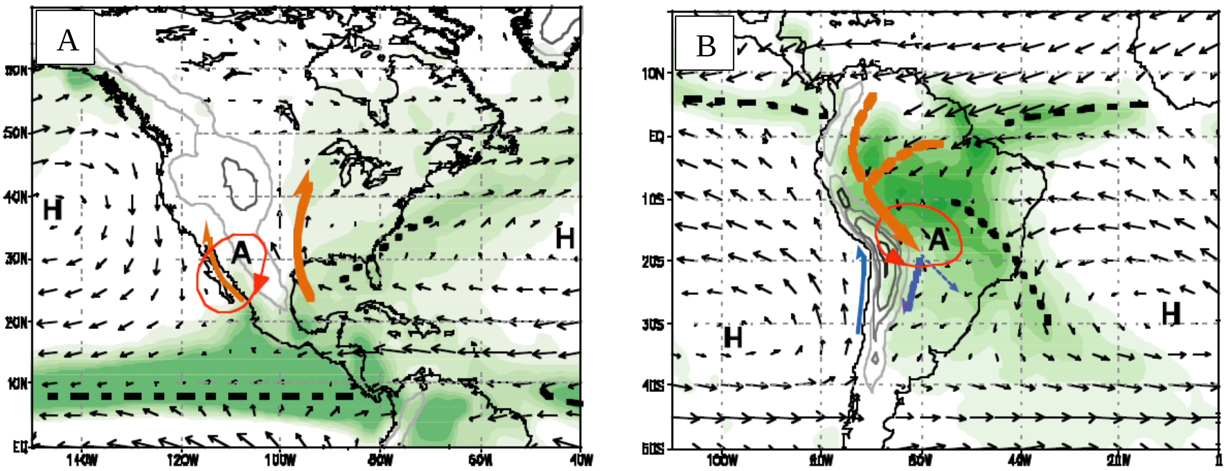


Figure 1. Schematic illustration of the: A) North American Monsoons Systems; and B) South American Monsoons Systems. "H" indicates a subtropical surface high center, and an "A" indicates the monsoon anticyclone (Mechoso et al., 2004).

As the understanding of climatic variability, both in the past and in the present, is a powerful tool for predicting the future climate (Reboita et al., 2021), the number of paleoclimatic studies in South America (SA) has increased. Different paleoarchives are used in this type of study, such as speleothems (e.g., de Godoy et al., 2021; Midhun et al., 2021), pollen (e.g., Cassino and Ledru, 2021; Smith et al., 2021), lake sediments (e.g., Cassino et al., 2020; Guzmán-González et al., 2020), and tree rings (e.g., Albuquerque et al., 2019; Macedo et al., 2020). However, although the number of studies in SA has increased, they are still quite scarce when compared to other regions, such as North America and Europe.

Lakes are valuable sentinels for global climate change, they are among the best and most sensitive continental indicators of environmental change (Adrian et al., 2009; Battarbee, 2000; Fritz, 1996). Thus, lake sediments are an important archive for reconstructing long-term fluctuations in environmental conditions (Elbert et al., 2013), with a time span of ~ 10^4 to 10^6 years (Bradley et al., 1999). The multiproxy approach has recently become a trend in these studies (Nowacki et al., 2019), since paleoenvironmental reconstructions using a single proxy are constrained by the limitations of that proxy (Ficken et al., 2002) and the multiproxy approach can provide more information about the climate system than the sum of individual proxies (Nowacki et al., 2019). Additionally, the appropriate combination of proxies allows the complementary strengths of each proxy to be exploited and the weaknesses to be identified (Mann, 2002). In addition to the proxies, an accurate dating and a reliable age model is essential in paleoclimatic studies, since the degree of success in discerning patterns of climate and environmental change depends on the level of correlation of paleorecords, which is related to the quality of the age model (Zimmerman and Wahl, 2020). Unfortunately, many of the studies carried out in South America have some limitations, such as the use of only one proxy and / or few dates that compromise the age models and make up less robust reconstructions.

1.1. Hypothesis

As the South America is an area under strong influence of a monsoon system, more than 50% of the total annual rainfall occurr during the summer, the understanding about the climatic system of this region is important for the maintenance of ecosystems, for the support for communities and for water regulation in large regions (Vera et al., 2006; Fu et al., 2013; Arias et al., 2015).The lack of more robust climate studies in this region has motivated the investigation of its climatic variations since the Holonene period through lake sediments. The hypothesis of this work is that the analysis of the lake cores records climatic and environmental variations at different scales, from continental to local scale.

1.2. Objectives

General Objective

The general objective of this dissertation is to analyze if the lake sediments can record climatic and environmental variations at different scales, from continental to local scale.

Specific Objetives

To achieve the general objective of this dissertation some specific objetives were defined, as described below:

1. Identify the mais proxies used in paleohidroclimate studies through lake sediments around the world, which relationships are most used and whether the interpretation of data varies according to the environmental and climatic context of each lake;

2. Understand the importance of the calibrated ^{14}C age models in paleohidroclimatic studies;

3. Investigate how the SAMS influenced in the SA paleoclimate since the Holocene period (last 12000 years) and how this system varied;

4. Investigate the influence of AMS in the climate of Central Brazil.

1.3. Structuring

This dissertation is composed of four scientific articles that are under review or in preparation. The first three articles are independently built compilations, each one with its own database, and the last article is a case study. Thus, both the materials and methods section (Chapter 2) and the results section (Chapter 3) are divided into these articles and in the final remarks and considerations section (Chapter 4) there is a discussion and general conclusion of the dissertation.

For a better understanding of this dissertation, the four articles that comprise it will be briefly described below:

The first article is entitled " PALEOCLIMATIC AND PALEOENVIRONMENTAL STUDIES IN LAKE SEDIMENTS: APPLICATIONS, EVOLUTION AND PROXIES " by Bianchini et al. and is under review. This article is a compilation of paleohydroclimatic studies based on lake sediments all over the world to identify the mais proxies used in paleohidroclimate studies through lake sediments around the world, which relationships are most used and whether the interpretation of data varies according to the environmental and climatic context of each lake.

The second article is entitled "*“A fully calibrated and updated Mid-Holocene Climate reconstruction for eastern South America*” by Gorenstein et al. and is in preparation. This article is an update in the compilation made by Prado et al. (2013) with the addition of new records and with the calibration of the uncalibrated ^{14}C age models showing the difference between the use of calibrated and uncalibrated ^{14}C age models in paleoclimatic studies.

The third article is from Bianchini et al. and is in preparation. This article is a compilation of paleohydroclimatic studies based on lake sediments in the influence zone of the AMS to investigate how the SAMS influenced in the SA paleoclimate since the Holocene period (last 12000 years) and how this system varied;

The fourth article is from Yokoyama et al. and is in preparation. This article is a case study with analysis made in samples from the LFB1 core, collected in Lagoa Feia, to investigate the influence of AMS in the climate of Central Brazil.

Chapter 2

Materials and methods

2.1. Paleoclimatic and Paleoenvironmental Compilation Data

In this study from Bianchini et al., a compilation of 195 paleoclimatic and paleoenvironmental studies carried out in lake sediments was produced, between the years 1985 and Jan/2020. These studies were randomly selected so that lakes were chosen from all over the world, in different climatic and environmental contexts. Different search tools were used in this compilation, such as Scopus, Google Scholar and Elsevier in which the keywords paleoclimate, paleoenvironmental and lake sediments were searched. A total of 410 lakes around the world were compiled with a focus on the paleoclimatic proxy types used. The structure and workflow of this study are depicted in Figure 2.

The designed database has information about the proxies used in each record, the location and altitude of the lakes, their dimensions, and estimates the water levels in the present day. These informations were obtained from Google Earth Pro (version 7.3.3) images analysis, from Jan/2019 to Jul/2020. After setting the database, all proxies were identified and classified into three types: biological, isotopic ratio and physicochemical. After the classification, each proxy was examined, considering how their use, their interpretations, and limitations based on the consider studies.

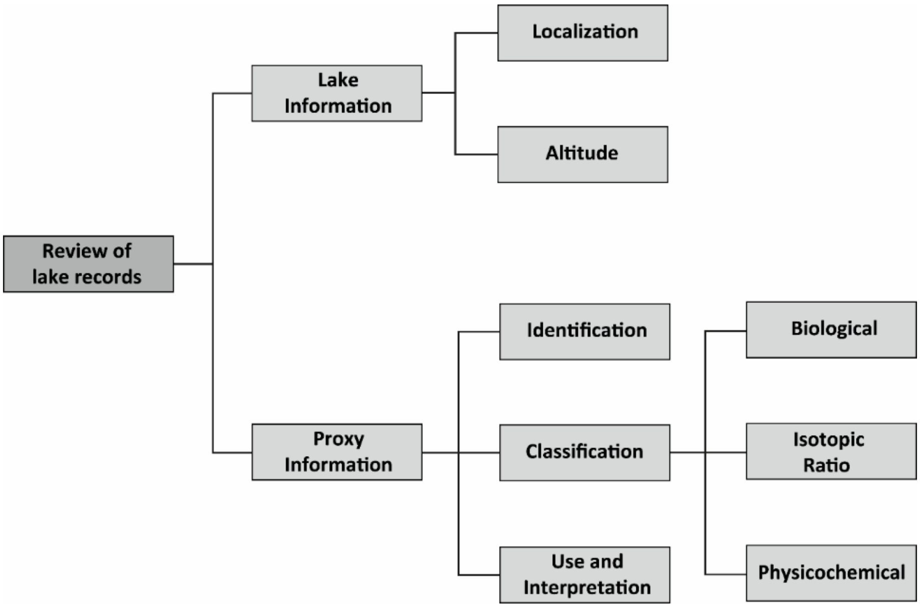


Figure 2. Workflow used in this study.

2.2. ^{14}C Age Calibration

In this study from Gorenstein et al. it was used a diffent dataset from the one used in the previous article. In this article an update of the paleorecords compilation of Prado et al. (2013) was made. Prado et al. (2013) presented a compilation of multiproxy palaeoclimatic data from the Middle Holonece (MH) for eastern South America including data from land, cave, lake, river, and ocean archives. The update was made including more recent records and calibrating age models that were uncalibrated.

For calibration, the studies examined by Prado et al. (2013) that had uncalibrated 14C age models were used, in addition to three other more recent studies that were chosen based on the same criteria used by authors, one temporal and the other spatial. These criteria establish that only data from the MH period (7000 to 5000 cal yr BP) and located in the area of interest (0°-40°S; 70°W-30°W) should be analyzed in this study. Therefore, a total of 51 paleoclimatological records were compiled from the analysis of 45 studies using the original published chronologies.

The age calibration was performed using Bayesian statistics with the BACON software (Blaauw and Christen, 2011). Bacon is an approach to age-depth modeling that uses Bayesian accumulation histories for deposits by combining radiocarbon dating with previous information. Bacon divides the core into several vertical sections, and through millions of Markov Chain Monte Carlo (MCMC) interactions, it estimates the accumulation rate (in years / cm) for each sections. These accumulation rates form an age-depth model and are limited by the program's input information (Blaauw and Christen, 2013).

A robust age model of Bacon requires the correct specification of prior information, and the correct use of each of the program parameters. The prior accumulation rate consists of a gamma distribution, much like a normal / Gaussian distribution, which is always positive and can be asymmetric. This prior accumulation rate has two parameters, acc.shape (default = 1.5) and acc.mean (default = 20, which can be changed according to the type of deposit), based on Goring et al. (2012). The section thickness (default = 5 cm, can be changed according to the particularity of each model) affects the flexibility of the age-depth model, the more sections, the smoother the model tends to be. The memory defines how much the accumulation rate of a given core depth depends on the depth above it. When that memory is low, it is assumed that the rate of accumulation has changed a lot over time, and when that memory is high, it is assumed that the rate of accumulation has been constant. Any hiatus (hiatus.depths = depth of hiatus) or boundaries (boundary = depth of boundaries) found in the core should also be considered (Blaauw and Christen, 2013). Figure 3 shows a Bacon output graph with their main parameters.

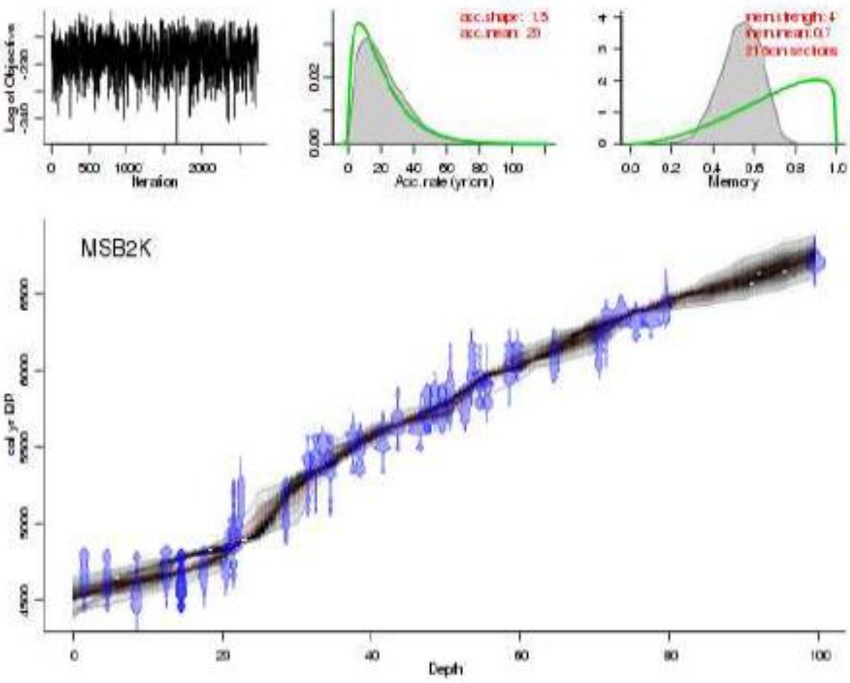


Figure 3. Bacon output graph. Upper panels depict the MCMC iterations (left panel), the prior (green curves) and posterior (grey histograms) distributions for the accumulation rate (middle panel) and memory (right panel). Bottom panel shows the calibrated 14C dates (transparent blue) and the age-depth model (Blaauw and Christen, 2013).

Bacon calibrates radiocarbon dates using different types of calibration curves, depending on the particularity of each data set. The standard ^{14}C calibration curve is IntCal13 (cc = 1). This curve can be changed to cc = 2 (Navy 13), cc = 3 (SHCal13), cc = 4 (an alternative curve), or cc = 0 (for calendar dates, which do not need to be calibrated). Post-bomb ^{14}C dates (with negative values) are calibrated using one of the post-bomb calibration curves (post bomb = 1 for NH1, 2 for NH2, 3 for NH3, 4 for SH1-2, 5 for SH3). There are also two parameters to indicate whether there was an age shift in the core, the mean age of the reservoir (delta.R or dR) and its associated 1 standard deviation error (delta.STD or dSTD) for each date in the core. These two parameters must be used together, and when there are no assumed offsets, these parameters will be equal to 0 (Blaauw and Christen, 2013).

For calibrations, the dates, and their respective depths in each of the cores were considered. When the depths referring to each dating corresponded to an interval, the mean of the depths was considered. When the depths referring to each dating were not present in the text, but in the figures of the article, these depths were obtained through the figures. A .CSV table was made with seven columns: identification of each sample (labID), age (years B.P.), error, depth (cm), cc (3), dR (0), dSTD (0). To interpolate the accumulation rates from the most recent date to the top, the core-top sample date was assigned as the core collection year, when there was no information about the sample collection date. The rate of accumulation of the lower core layer was estimated to be the same as that obtained for the oldest depth (e.g. Garnier et al., 2020).

The calibrations performed resulted in the minimum, maximum, average, and median ages for all depths between the depth of the most recent dating (the top) and the depth of the oldest dating of each core. A final table was made with the original published chronologies data, adding the results obtained by the calibration of the ages. When the depths considered for the calibration were obtained by an average, the ages calibrated for these depths were obtained by means of the average of the obtained ages.

2.3. American Monsoon System (AMS)

In this study, information from paleoclimatic and paleoenvironmental studies from lake sediments was compiled. This compilation is composed of lakes that recorded the changes of the AMS during the Holocene (last 12000 years).

Four main criteria were used to select the studies included in this compilation. The first one is the spatial domain, defined based on characteristics of the AMS. The latitudinal limits used are from 40°N to 40°S, and the longitudinal limits used are from 120°W to 30°W, as shown in

Figure 4.

These limits determine the area of influence of the North and South American Monsoon System (Vera et al., 2006), constituting the area of action of the AMS. Secondly, it was considered only studies with two or more proxies, once no single proxy is adequate to reconstruct large-scale patterns from the past climate (Mann, 2002), and the multiproxy approach can provide more information about the climate system than the sum of the individual proxies since the interpretation based only on a parameter or proxy can be misleading and may not address all the complexity of the system (Nowacki et al., 2019).

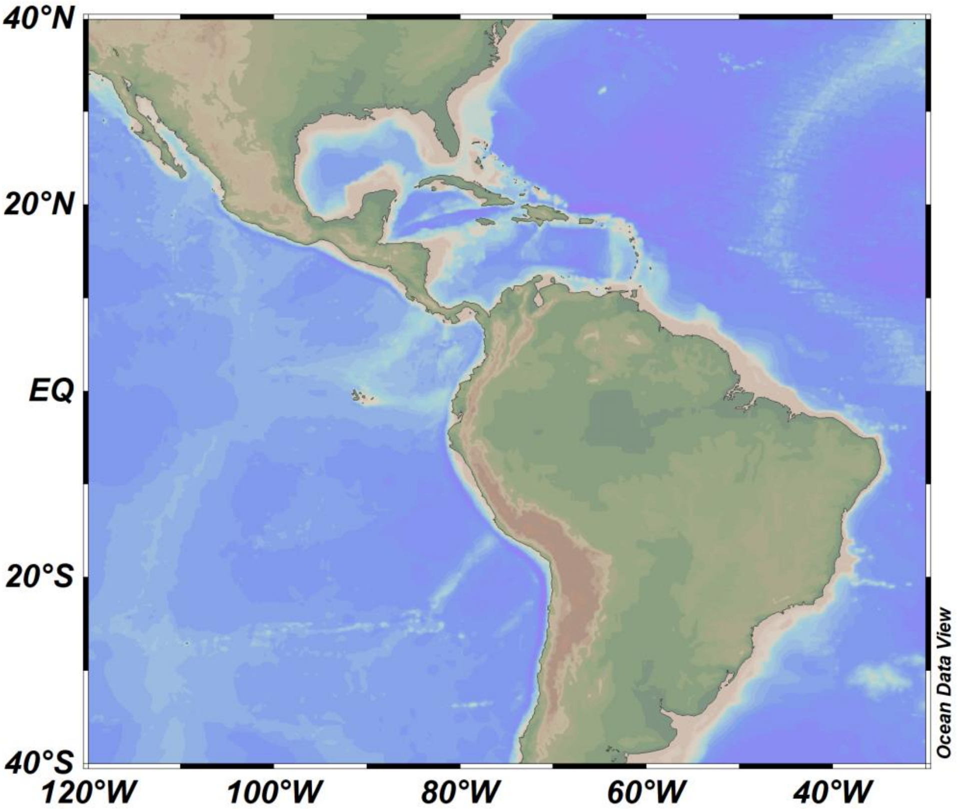


Figure 4. Map with the special domain used in this study.

Thirdly, it was considered only studies with calibrated ages, once the calibration compensates for the error introduced by the conventional half-life (Libby ages) and the temporal variability of the atmospheric ^{14}C content (Hajdas, 2008). Moreover, calibrated ages can provide a linear age scale on which other chronologies (e.g., ^{210}Pb, ^{137}Cs) can be combined (Birks and Birks, 2006). And fourthly, we considered studies about the Holocene period. The Holocene cover the time interval from 11.7 ka B. P. until the present (Walker et al., 2012). In the present research was considered studies dating between 12,000 and 1,850 cal years C.E., to avoid anthropic actions from recent periods. These criteria were determined so that there was a temporal space consistency in the lake records with respect to the performance of the AMS.

The data obtained were compared with the current AMS mean pattern (mean precipitation during summer) and with the summer insolation curves in Northern and Southern America. To obtain the current AMS mean pattern, it was used monthly precipitation from the Global Precipitation Climatology Project (GPCP) v2.3 combined dataset (Adler et al., 2018). This observational dataset integrates satellite, soundings and gauge data, resulting in precipitation estimates over land and ocean. The different datasets composing the GPCP have been merged in a 2.5° x 2.5° resolution grid, dating from January 1979 to the present. To obtain the summer insolation curves it was used data from Berger and Loutre (1991) available at https://www.ncdc.noaa.gov/paleo-search/study/577.

2.4 Case Study: Lagoa Feia

The new record presented in this study was obtained from the analysis of the LFB1 core, collected in Lagoa Feia, located near the city of Formosa (GO) (Figure 5). This core is about 6m long and was collected in the 1990s by Dr. Maria Léa Salgado-Labouriau (*in memorian*) using the *Vibracore* sampling system. The core was opened on April 10, 2017 at the Laboratório de Geoquímica e Água, Instituto de Geociências, Universidade de Brasília (LAGEQ-IG-UnB).

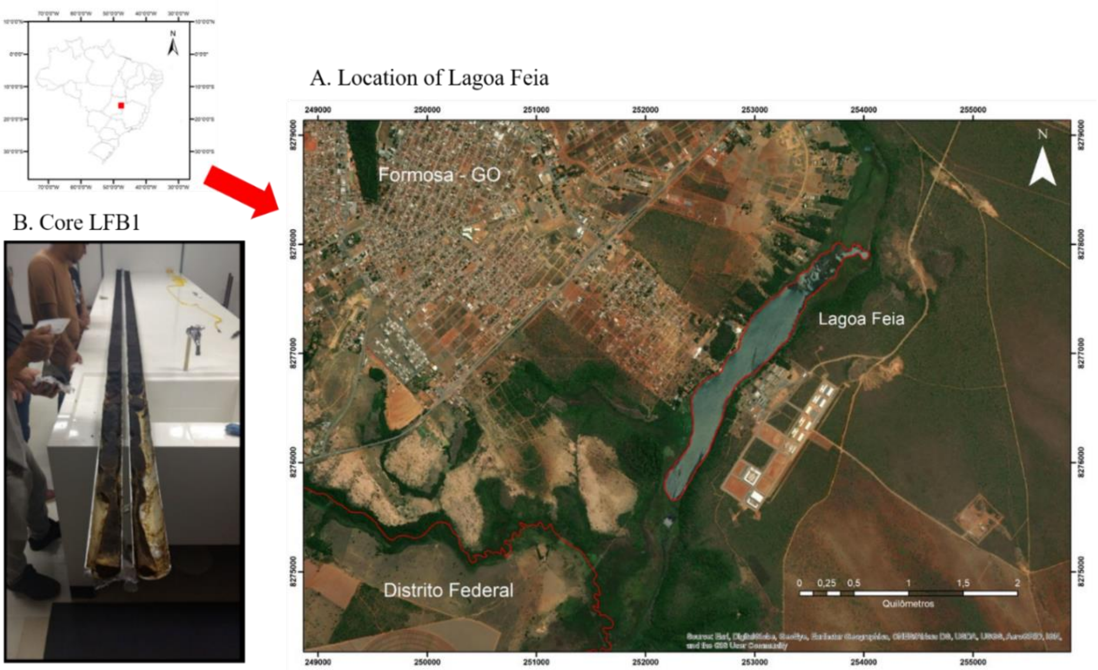
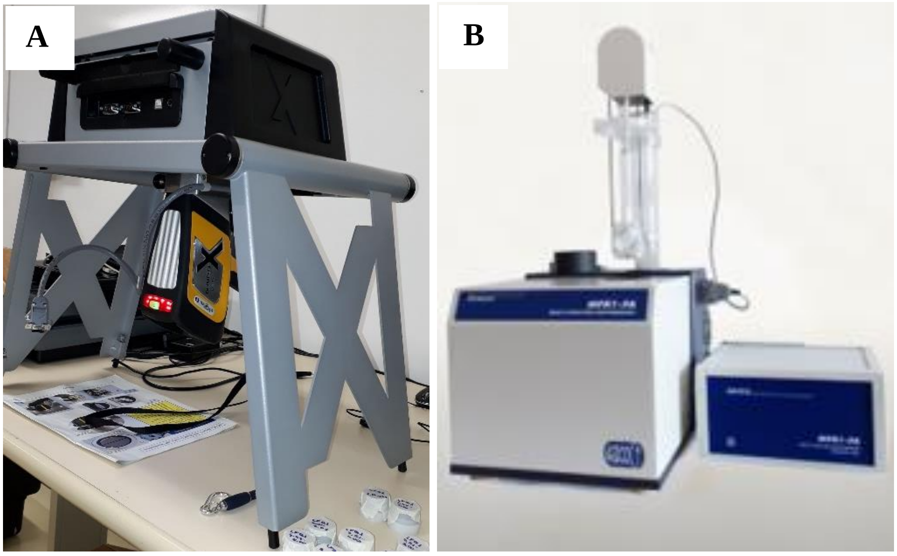


Figure 5. A. Map with the location of Lagoa Feia. B. Opened core LFB1 showing the top with alterations.

For the elementary analysis, sampling was made at intervals of about 50 cm, and 166 samples were analyzed. The samples were macerated in agate drumsticks, and fractions smaller than 0.180 mm were separated with the aid of an 8X2 "INOX ASTM 80 MESH / TYLER 80 by Bertrand sieve. These fractions were placed in XRF sample holder cups, with about 1cm of sample in each cup. The analyzes were made by X-Ray

Fluorescence, with the portable XRF DELTA Family, from Olympus, yielded by IG-UnB (Figure 6.A.). We used the soil mode with three repetitions of two minutes in each sample, and we considered their mean for the interpretation of the data obtained. For the analysis of the results, the elementary ratios Ca/(Al+Fe+Ti), Ca/Fe, Fe/Ti, Si/Ti, Ti/Ca and Ti/K were used to avoid artifacts generated by possible dilutions of carbonates or organic matter (e.g., Löwermark et al., 2011).

For the magnetic analysis, sub-sampling was made in the central part of the half pipe, to avoid the collection of sediments from the edge of the core, which may have undergone movement during the core control, causing the reorientation of the grains. Sub-sampling was performed discreetly, in cubic boxes with a volume of approximately 8 cm^3 at intervals of about 3 cm, and 142 samples were measured. Magnetic susceptibility (MS), Natural Remanent Magnetization (NRM) and Anhystereic Remanent Magnetization (ARM) measurements were made. The MS was measured in its high and low frequencies, to characterize superparamagnetic behaviors, and the measurements were made in the MFK-1 (Agico) multi-frequency susceptibility meter (Figure 6.B). The NRM is the record of all the magnetizations that the rock has registered since its formation, and the ARM represents the magnetization induced in the laboratory and assists in the identification of the type and size of the magnetization carrier (Wei et al., 2018). Both NRM and ARM measurements were made on the Long Core 2G Cryogenic superconducting magnetometer (Figure 6.C). The magnetic measurements were made at the Laboratório de Paleomagnetismo of the Universidade de São Paulo (USPMAG).



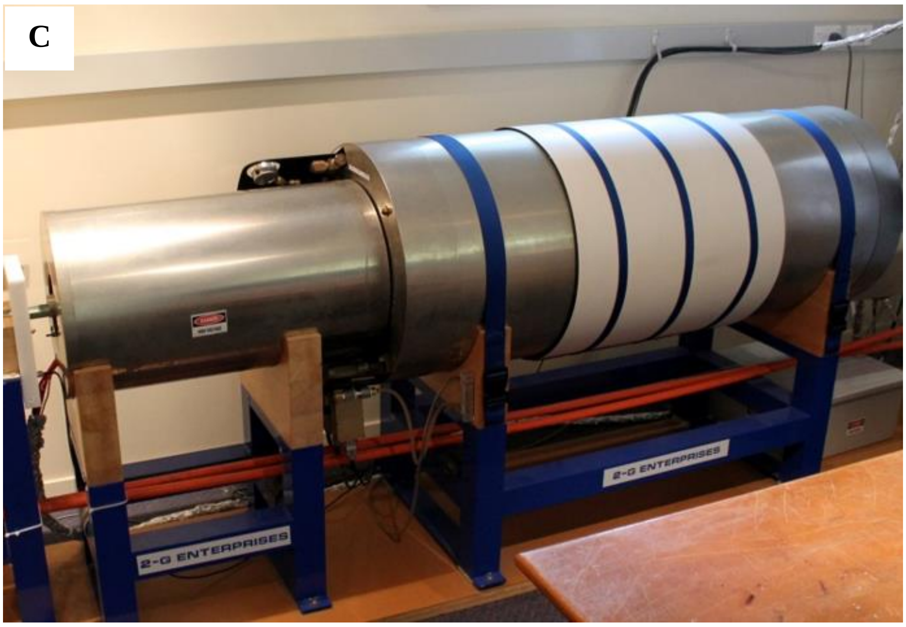


Figure 6. Equipment used in the elementary and magnetic analyzes. A. Portable XRF DELTA Family, from Olympus; B. MFK-1 (Agico) multi-frequency susceptibility meter; C. Long Core 2G Cryogenic superconducting magnetometer

To determine the global relationship between elemental ratios and magnetic proxies, a principal component analysis (PCA) was performed on the dataset using a sklearn library of python. The ^{14}C ages were obtained using the Accelerator Mass Spectrometry (AMS) radiocarbon dating at the French *Laboratoire de Mesure du Carbone 14* and the material used were sediments rich in organic matter. As Turcq et al. (2002) performed analyzes and dating in the twin core of the subject analyzed in this work, a combined age model was calculated using the Turcq et al. (2002) data and the five new ages, although the reduced number of dates limit the construction of a robust age model. Calibrated ages were obtained using Bayesian statistics with the BACON software (Blaauw and Christen, 2011), and the SHCal13 calibration (Hogg et al., 2013) for the Southern Hemisphere, as described in item 2.2.

Chapter 3

Results

3.1. Paleoclimatic and Paleoenvironmental Compilation Data

The results of this item compose the manuscript entitled "PALEOCLIMATIC AND PALEOENVIRONMENTAL STUDIES IN LAKE SEDIMENTS: APPLICATIONS, EVOLUTION AND PROXIES", from Bianchini et al. that is under review.

This compilation aims to understand the use and interpretation of paleoclimatic and paleoenvironmental proxies in lake archives. There have been identified the main proxies used in the studies considered, seeking to understand the applications and limitations of each one, according to the environmental and climatic context of each lake.

3.1.1. Highlights

- The same proxy can have different interpretations according to the lake's context;
- Changes in the lake environment affect different proxies in different ways;
- Different proxies' approaches were developed and improved over time;
- Proxies uses have evolved differently in the Northern and Southern Hemispheres;
- Multiproxy analyses compensate for the limitations of individual proxies.

3.1.2. Article

PALEOCLIMATIC AND PALEOENVIRONMENTAL STUDIES IN LAKE SEDIMENTS: APPLICATIONS, EVOLUTION AND PROXIES

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Abstract

Lakes constitute an important archive for to reconstruction of paleoclimate and paleoenvironment. Lacustrine sediments are continental indicators sensitive to environmental changes that can be used in high temporal resolution reconstructions of past climate conditions, land management, flood events, pollution due to mining activities, and environmental or limnological lake conditions. Different proxies have been used in paleoclimatic and paleoenvironmental reconstructions with lake sediments, with their inherent time range and resolution, advantages, and limitations. In this paper, we present a multiproxy compilation of paleoclimatic and paleoenvironmental reconstructions based on lake sediments covering all continents but Antarctica. We compiled 195 publications, dating from 1985 to 2020 correspondent to 410 lakes all over the world, and analyzed the main types of proxies used in these studies. We identified diatom analysis, organic matter, pollen analysis, isotopic ratios of carbon, nitrogen and oxygen, elementary analysis and inorganic ratios, environmental magnetism, and grain size analysis as the main proxies used in these publications. We classified these proxies in three main types: biological, isotopic ratio and physicochemical, and examined their application, limitation and correlation in different climatic and environmental contexts. It was possible to observe that, although lakes are available all over the world, Northern Hemisphere (NH) records studies are more abundant. We also observed an evolution in the use of these proxies over time, from predominantly biological to multiproxy approaches, with development and improvement of statistical, numerical and chronological technologies and methodologies, and the association of different methods to obtain more complete age models. In addition, we noticed that the interpretation of the data obtained through these proxies should be made with caution, since the same result can have different interpretations according to the environmental and climatic context of each lake. In this case each lake context (e.g. regional/local climate, geology, geomorphology) should always be considered. Also, the limitations of each proxy must be considered, besides those limitations can be compensated with the use of a different proxy through a multiproxy approach. A multiproxy approach could then provide potential independent evidence with complementary proxies, or that reaffirm themselves, contributing to more complete studies.

Keywords: Compilation, lacustrine sediment, multiproxy

1. Introduction

Lakes are valuable sentinels for global climate change as they are among the best and most sensitive continental indicators of environmental change (e.g. Adrian et al., 2009; Battarbee, 2000; Fritz, 1996). Lakes sediments can provide continuous and sensitive records of changes in conditions and processes within lakes themselves and in the surrounding basin (Eris et al., 2018). Lacustrine sediments constitute an important archive for reconstructing long-term fluctuations in environmental conditions (Elbert et al., 2013), with a temporal range from ~10^4 to 10^6 years (Bradley et a., 1999). The main environmental changes recorded in lake sediments are climatic, vegetation or land cover, changes in sea level, tectonic activity and aquatic biota (Cohen, 2003), in addition to anthropogenic activities (Miller et al., 2014). Therefore, lake sediments have been widely used to reconstruct past climate conditions (e.g. Sun et al., 2019; Xiao et al., 2018), land management (e.g. Reavie et al., 2017), previous flood events (e.g. Corella et al., 2014; Kämpf et al., 2012), mining pollution (e.g. Guyard et al., 2007; Miller et al., 2014;), and the lake's environmental or limnological conditions (e.g. Hodelka et al., 2020; Panagiotopoulos et al., 2020). Additionally, environmental changes cause variations in the dynamics of the drainage basin, that are accurately registered in the lake sediments (Fierro et al., 2016; Giralt and Julià, 2003).

In studies dealing on lakes sediments, several proxies have been used to reconstruct paleoclimate and paleoenvironmental changes from lake sediments. The most commonly used are diatom analysis (e.g. Babeesh et al., 2019; Gomes et al., 2014; Schwarz et al. 2017); organic matter (e.g. Lorente et al., 2018; Nowacki et al., 2019; Zocatelli et al., 2012); pollen analysis (e.g. Cassino et al., 2020; Kılıç et al., 2018; Kousis et al., 2018Smon et al., 2020); carbon isotopic ratio (e.g. Fiers et al., 2019; Morellón et al., 2018; Saini et al., 2017); nitrogen isotopic ratio (e.g. Gayantha et al., 2017; Hodelka et al., 2020; Zular et al., 2018); oxygen isotopic ratio (e.g. Anderson et al., 2018; Grauel et al., 2016; Sun et al., 2019); elementary analysis and inorganic ratios (e.g. Kylander et a., 2011; Speranza et al., 2019; Yan et al., 2020); environmental magnetism (e.g. Demory et al., 2020; Morales et al., 2019; Wei et al., 2018); grain size analysis (e.g. Castro et al., 2019; Mishra et al., 2019; Zhou et al., 2018), among others.

In addition to long time variation, lakes have global spatial distribution, which contributes extensively to their utility as sentinels. In this way, lakes can provide a way to detect and monitor the effects of climate change on the scale of the ecosystem, in locations that are underrepresented in climate studies or are influenced by other environmental changes (Adrian et al., 2009). As an effort to compile spatial and temporal lakes changes along time, global databases have been developed. The Global Lake Status Data Base (GLSDB) assessed lake level or relative water depth (state of the lake) over time (30,000 BP years to date) based on a consensual interpretation of the physical, chemical and biological data available from exposed cores or sections (GLSDB, 2010). The World Lake Database, which contains scientific and socioeconomic data on the environments of various lakes around the world (WLDB, 2020); and the National Centers for Environmental Information (NCEI) that hosts and provides public access to one of the most significant archives for environmental data on Earth. The NCEI brings together databases with different types of information, such as pollen (e.g. BIOME 6000, 2001), and lake level (e.g. Anderson et al., 2018; Liu et al., 2016; NCEI, 2020).

Many of these databases or studies explore a specific characteristic of the lake in different environmental contexts, which can limit the interpretation in some cases since any paleoenvironmental or paleoclimatic reconstruction using a single method is restricted by the limitations of that proxy itself (Ficken et al., 2002). The effectiveness of lakes as sentinels for climate change depends on our understanding of the lake's internal processes (Adrian et al., 2009) and, as the environment affects different proxies in different ways, as the deficiencies of one proxy can be compensated for by others (Kiage and Liu, 2006). Therefore, the simultaneous study of several proxies, the so-called multiproxy approach (Birks and Birks, 2006), allows for a more consistent and accurate reconstruction of paleoclimate and paleoenvironmental changes in the watershed (Boyd and Hall, 1998; Hausmann et al., 2011; Smol and Cumming, 2000) than the analysis of only a single variable (Enters et al., 2010).

To contribute to a more comprehensive understanding of the use and the interpretation of paleoclimatic and paleoenvironmental proxies in lacustrine archives, we performed a review of proxy use and analysis in studies based on lake sediments. This resulted in a database with 410 lakes all around the world and 195 publications. The main goal of this study was an analysis of the major proxies used in the studies, seeking to understand the applications and limitations of these proxies according to the environmental and climatic context of each lake. Nine groups of proxies were examined: diatoms, organic matter, pollen, isotopic ratios of carbon, nitrogen and oxygen, elemental analysis, and inorganic ratios, environmental magnetism, and grain size. In addition to the database and analysis of these proxies, the present study aims to identify the best approach analyzing the factors that influence the effectiveness and interpretation of these proxies, promoting a diagnosis of the evolution over time, and finnaly verifying the advantages of the multiproxy approach. Thus, this paper provides information that will assist future studies, promoting more objective analyzes and more robust paleoclimatic and paleoenvironmental reconstructions.

2. Data and Methods

In this study, a compilation of 195 paleoclimatic and paleoenvironmental studies carried out in lake sediments was produced, between the years 1985 and Jan/2020. These studies were randomly selected so that lakes were chosen from all over the world, in different climatic and environmental contexts. Different search tools were used in this compilation, such as Scopus, Google Scholar and Elsevier in which the keywords paleoclimate, paleoenvironmental and lake sediments were searched. A total of 410 lakes around the world, taking into account all continents and climatic conditions, were compiled with a focus on the paleoclimatic proxy types used. The structure and workflow of this study are depicted in Figure 7.

The designed database has information about the proxies used in each record, the location and altitude of the lakes, their dimensions, and estimates the water levels in the present day. These informations were obtained from Google Earth Pro (version 7.3.3) images analysis, from Jan/2019 to Jul/2020.

After setting the database, all proxies were identified and classified into three types: biological, isotopic ratio and physicochemical. After the classification, each proxy was examined, considering how their use, their interpretations, and limitations based on the consider studies.

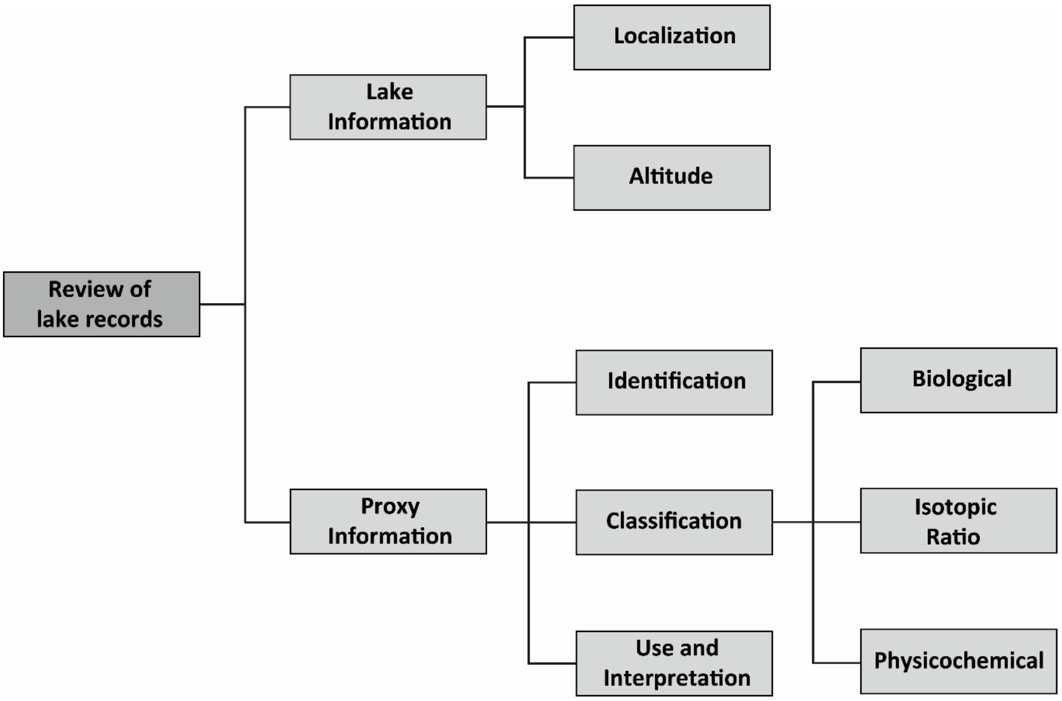

Figure 7. Workflow used in this study.

3. Results

3.1. Compilation Results

All studies considered are presented in Table 1 (Appendix I), where the lakes are grouped according to the continent they are located, name of the lake, geographical coordinates (latitude and longitude), altitude, types of proxy used (P), and correspondent references. Other data such as the largest lake measurement, present-day water level, and dating methods used are available in Table S1.

Table 2 (Appendix I) shows the number and percentage of lakes studied on each continent, also represented in

Figure 8. The geographic distribution of the lakes is displayed in

Figure 9 combined with the types of proxy (P) used in each study. Table 3 (Appendix I) shows the number and the percentage of lakes that used each type of proxy, separated by continents, and this information is displayed in Figure 10. And Table 4 (Appendix I) shows the number of lakes studied at each altitude.

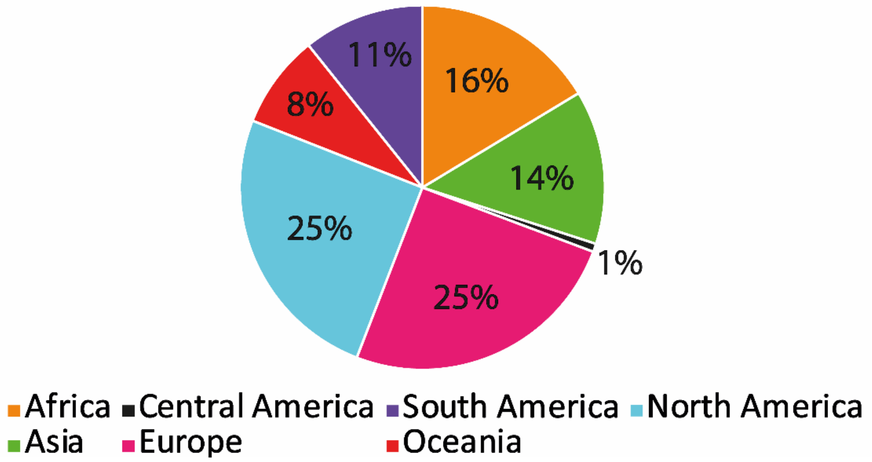

Figure 8. Relative amount of lakes used in this study per continent. Colors refer to each continent.

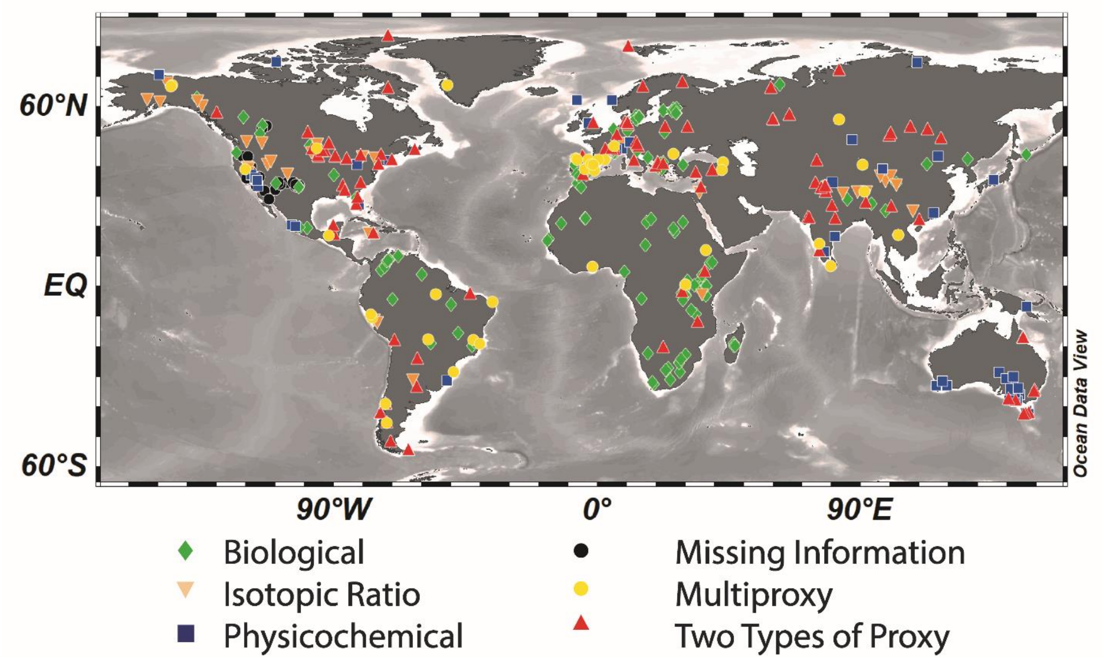

Figure 9. Spatial distribution of the 410 lakes considered in this study according to proxy type (symbols and colors).

Results are shown in Table 2 (Appendix I) and

Figure 8 and

Figure 9, show that more than 60% of the studied lakes are in the Northern Hemisphere. Most studies in the NH (about 30%) use at least two proxies, while in the Southern Hemisphere, most of the studies (about 55%) use biological proxies only (Table 3 - Appendix I and Figure 10). Thus, the discrepancy in both the quantity and the types of proxy most used in each continent is visible, since in the Northern Hemisphere, there is a greater number of lakes and studies with a more comprehensive approach using more varied proxies, while in the Southern Hemisphere (SH) there are fewer lake records, where single proxy approaches are more common. The classification of the studies in relation to altitude shows that 65% of the studied lakes are located under 1000 meters of altitude, 33% is between 1000 and 5000 meters, and less then 1% is above 5000 meters (Table 4- Appendix I). This may be because there are more lakes at lower altitudes, and because these lakes are more accessible than those at higher altitudes.

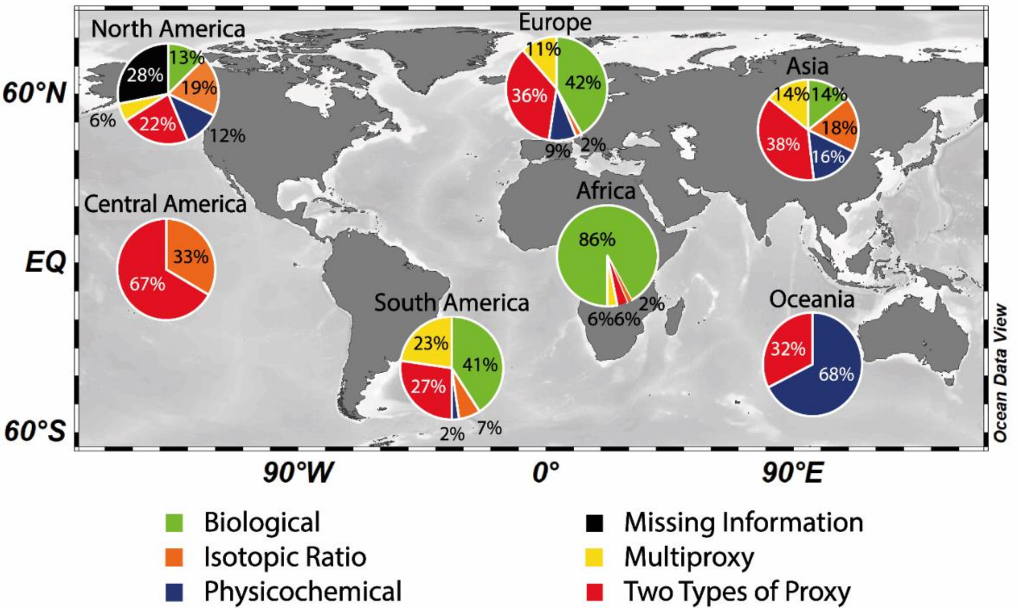

Figure 10. Distribution map of proxy used by continent.

3.2. Proxy Classification

The compilation allowed the identification of several proxies used in paleoclimatic studies based on lake sediments. In this study, we address some of them, grouped into three types: biological, isotopic ratios, and physicochemical proxies. Table 5 (Appendix I) displays the types of proxy used in our compilation. The classification presented was based on Prado et al. (2013) (see Table 1 in Prado et al. (2013) for more details). Biological proxies are those that present information derived from living organisms (e.g., diatoms), organic matter, and pollen. Isotopic ratio proxies are mainly carbon, nitrogen and oxygen stable isotopic ratios. Physicochemical proxies are grain size, chemical elements and their ratios and environmental magnetism, that include all geochemical and physical-chemical approaches. The classification and correlation between the types of proxy used in this study are outlined in Figure 11. The correlation presented was made by relating the proxies that were used in association, to obtain complementary information, in the considered studies. Some of the compiled proxies have generalized interpretations and exceptions can be readily found in the cited references.

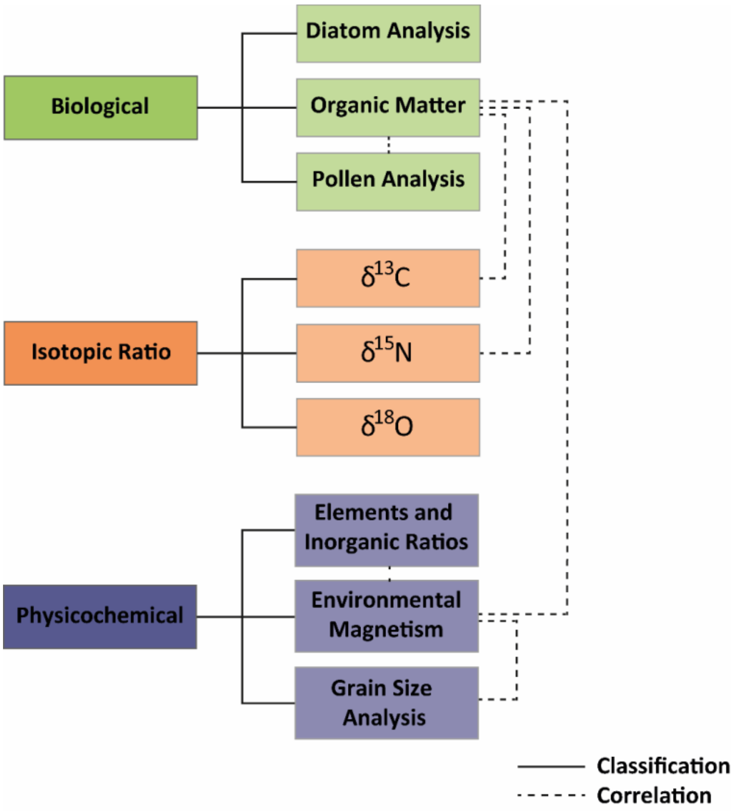

Figure 11. Flowchart of classification and correlation of the analyzed proxies. Details of the classification are displayed in Table 5 (Appendix I).

3.2.1. Biological

3.2.1.1. Diatom Analysis

Diatoms contribute to a substantial portion of primary production in lakes (Veena et al., 2014). Because of their siliceous composition, diatoms have a high preservation potential in lacustrine environments, particularly fine-grained sediments that minimize the damage of the diatom count (Anderson, 1997; Lowe and Walker, 1997; Stoermer and Smol, 1999; Gehrels, 2007). Their diverse taxonomy coupled to the preservation potential makes diatoms a very useful proxy for the paleoenvironmental reconstruction of long-term change, but their short lifespan and ability of rapid rebirth also allow for their application in understanding centennial-scale climatic changes (Leblanc et al., 2005; Bradbury, 1997).

Analysis of diatoms in paleoclimatic studies is generally associated with the identification and nomenclature of diatoms (e.g. Babeesh et al., 2019), quantitative methods for estimating their concentration (e.g. Vossel et al., 2018), and groups according to their ecological and habitat preferences (e.g. Panagiotopoulos et al., 2020). From these analyses, authors inferred lake information such as depth (e.g. Panagiotopoulos et al., 2020), trophic state (e.g. Maslennikova and Udachin, 2017; Maslennikova et al., 2016; Panagiotopoulos et al., 2020), and salinity (e.g. Laird et al., 1998; Pienitz et al., 2000).

In general, due to their thick cell walls and high nutrient requirements, it is expected that the abundance of diatoms decreases as temperature increase because of greater competition for nutrients and increasing sinking velocities, which also favors the increase of small diatoms cells (Winder et al., 2009). This proxy can be used in paleoclimatic studies to reconstruct the level of the lakes, and their rate of productivity, as was done in Lake Kinneret (Israel) (LRN 91), by Vossel et al. (2018) to study Holocene regional paleoclimate variability, and also to interpret the water mixing rate, related to the wind speed, as was done in Manasbal Lake (India) (LRN 107), by Babeesh et al. (2019) to study Late Holocene paleoenvironmental changes.

3.2.1.2. Organic Matter

Organic matter in sediments originates from the complex mixture of lipids, carbohydrates, proteins, and other biochemicals produced by organisms that live both in the lake and in its watershed (Meyers and Ishiwatari, 1993; Meyers and Lallier-Verges, 1999). Organic matter in lake sediments provides information such as changes in the type and abundance of plant life in and around the lake (Sandeep et al., 2017). This information allows analyses of the lake paleoenvironment, historical of climate change, and the effects of human beings on local and regional ecosystems (Meyers and Lallier-Verges, 1999). Despite the fact that lake systems are diverse, and the sources and changes in organic matter are geographically and temporally variable (Meyers and Lallier-Verges, 1999), the advantage of lake organic proxies is that the short-term processes that affect the delivery and burial of organic matter are amplified in the sediment record due to the high sedimentation rate and the high primary productivity in lakes (Meyers, 2003).

We have identified five organic matter parameters that are applied in paleoclimatic reconstructions in lake sediments. Their information and environmental interpretation are summarized in Table 6 (Appendix I). Total organic carbon (TOC) content is important to characterize the abundance, production, and degradation of organic matter in lake sediments (Burdige, 2006; Martín-Puertas et al., 2011; Meyers, 2003; Meyers and Lallier-Verges, 1999). This proxy can be calculated as the difference between total carbon (TC) and total inorganic carbon (TIC) (e.g. Burdige, 2006; Damaschke et al., 2013; Stansell et al., 2013). The contents of TOC present in lakes generally vary through sedimentary sequences, indicating changes in an organic deposition under different sedimentary conditions (e.g. Chassiot et al., 2018; Guerra et al., 2017). Therefore, TOC content in lake sediments is a useful proxy for paleoenvironmental reconstruction, reflecting the climatic conditions and the environment of the lakes (Yanhong et al., 2006). Total nitrogen (TN) content usually allows an interpretation of a terrestrial or lacustrine origin of the organic material (Cohen, 2003), as for example through the TOC/TN ratio (Meyers, 1994; 2003). The C/N ratio in sediments is often used as a proxy to identify organic matter sources, evaluate diagenetic alteration and paleoenvironmental conditions prevalent in a particular region (Meyers and Ishiwatari, 1993; Meyers and Lallier-Verges, 1999; Talbot and Lærdal, 2000). Values of C/N around 8 commonly suggest a phytoplankton source for organic matter, whereas C/N ratios around 20 are attributed to the input of macrophytic margin vegetation or terrestrial plant material (Meyers and Lallier-Verges, 1999; Viana et al., 2014). This proxy can be used in paleoclimatic studies to reconstruct the paleoenvironmental changes around the lake area, as was done in Manasbal Lake (India) (LRN 107), by Babeesh et al. (2019) to study Late Holocene paleoenvironmental changes, and also as a high-resolution archive of deglacial environmental information, as was done in Mono Lake (United States) (LRN 279), by Hodelka et al. (2018) to study paleoproduction and environmental changes.

3.2.1.3. Pollen Analysis

Among biological proxies, palynology has been increasingly used to understand the paleovegetation and paleoclimate of the Quaternary (Raj et al., 2015), once the study of fossil and modern pollen assemblages provides essential information about vegetation dynamics in space and time (Martin and Harvey, 2017). Pollen analysis can be used to reconstruct the Late Quaternary and Holocene paleoenvironments in a variety of sediments, including lake mud (e.g. Sadori et al., 2016), sand dunes (e.g. Horrocks et al., 2000), tephra sections (e.g. Sase et al., 1987), coastal plain sequences and other sediments (Veena et al., 2014), because of their abundance and sensitivity to environmental variables (Brown, 1984; Mulholland, 1989). Pollen data offer the advantage of giving information not only on temperature but also on precipitation because plant distributions respond to changes in summer and winter temperature, and moisture balance (Prentice et al., 1992). In lake sediments, this analysis can be used, for example, to determine when the catchment area became forested and when the forest retreated (Jones et al., 2011).

Analysis of pollen in paleoclimatic studies generally starts with the identification and nomenclature of the collected material according to reference collections and photographic books (e.g. Bali et al., 2016; Chassiot et al., 2018; Demory et al., 2020; Goman et al., 2017; Speranza et al., 2019). After identification, several analyses can be performed in the pollen grains. One of them is the modern analog method, that consists of locating the closest modern analogs of each fossil pollen spectrum in a large set of surface samples using the chord distance measure to indicate the degree of analogy. The distance measure is modified by taxon weightings derived from a multivariate analysis of the fossil pollen data set (Harrison et al., 1993). This method has been used to reconstruct past temperature and precipitation from pollen data (Magny et al., 2001). However, it tends to be particularly challenging for people who are starting their studies in this area since the reference material normally used contains a regional scope, is incomplete or is in museums and research institutions, where access is limited (Martin and Harvey, 2017). Seeking to mitigate these issues, it was created the Global Pollen Project (GPP), an online database, open and reviewed by pollen data pairs from around the world, which provides a direct and easy connection from pollen grains to occurrences of more than 1,500 species of plants, and that can be used in these studies (GPP, 2017).

It is also possible to obtain pollen concentrations (e.g. Masi et al., 2018; Morellón et al., 2016; Stebich et al., 2015; Zhao et al., 2015), percentages (e.g. Aufgebauer et al., 2012; Engels et al., 2016; Leipe et al., 2014; Miebach et al., 2016; Xiao et al., 2018), relative frequencies (e.g. Bali et al., 2016; Chauhan et al., 2013; Speranza et al., 2019), providing frequency diagrams. Pollen diagrams are draw against both depth and timescales (e.g. Kılıç et al., 2018; Kulesza et al., 2012; Mehrotra et al., 2019; Ranhotra et al., 2018; Sadori et al., 2016; Stebich et al., 2015; Zernitskaya et al., 2015) and can also be divided into different pollen zones (e.g. Bhattacharyya et al., 2015; Chauhan et al., 2013; Kulesza et al., 2012; Nazarova et al., 2017; Ranhotra et al., 2018). The pollen zones can also be based on concentration data (e.g. Ghosh et al., 2014; Fedotov et al., 2012; Kılıç et al., 2018). This proxy can be used in paleoclimatic studies to obtain information on the dynamics of vegetation and, therefore, on the climatic variability of the region where the lake is located, as was done on Lake Ohrid (Albania and Macedonia) (LRN 189), by Kousis et al. (2018) to study Centennial-scale vegetation dynamics and climate variability in SE Europe during Marine Isotope Stage 11. In addition, there are pollen databases that feed climate models, such as BIOME 6000, which translates pollen assemblies into vegetation reconstructions, with the classification of individual pollen taxa into functional types of plants, the characterization of the main types of vegetation according to its characteristics or definitions and the application of an algorithm to select the most likely biome (Harrison, 2017).

3.2.2. Isotopic Ratio

3.2.2.1. Carbon Isotope ($\delta^{13}C$)

Isotopic carbon ($\delta^{13}C$) composition of bulk organic matter is commonly used in paleoenvironmental studies when preserved (Bird et al., 2020). This parameter tends to be used as a complementary proxy to long-term environmental analysis (Ghosh et al., 2014), often in conjunction with other geochemical information (Bird et al., 2020), such as organic matter analysis for example.

The interpretation of carbon isotopes of sedimentary organic matter in freshwater lakes is complex, requiring information on nutrient input, lake volume, productivity, groundwater input, and stratification, among others (van Hardenbroek et al., 2018). Nevertheless, these isotopes can provide information about the effects of changing organic matter source, reservoir composition, and diagenetic alteration (Noble et al., 2016). This proxy also provides information about changes in vegetation, productivity, water balance and methanogenesis, and allows reconstructions of the carbon cycle (Anadón et al., 2006; Bridgwater et al., 1999; Burnett et al., 2011; Horton et al., 2016; Li and Liu, 2014; Schwalb et al., 2013; van Hardenbroek et al., 2018). We identified that the presence of $\delta^{13}C$ in lake sediments and their values are commonly used environmental proxies. The values found can be indicative of the predominant source of organic matter present in the sediments, and for this reason, their variations allow for environmental interpretations. More negative values of $\delta^{13}C$ may indicate a decrease in algal productivity wich can indicate wet and coller conditions (e.g. Gayantha et al., 2017; Noble et al., 2016), while more positive values of $\delta^{13}C$ may indicate an increase in algal productivity wich can indicate drier conditions (e.g. Gayantha et al., 2017; Sandeep et al., 2017). The complete environmental interpretation of isotopic carbon ratios according to the dominant source is summarized in Table 7 (Appendix I).

Isotopic stable carbon composition of organic matter in lakes depends on the predominance of its sources, derived from the landmark or from within the lake (Sandeep et al., 2017). In general, terrestrial plants have two main modes of photosynthetic pathways, the C3 and C4 cycles (Ghosh et al., 2014). C3 plants (algae and trees), characteristic of humid environments, produce organic matter with $\delta^{13}C$ between -25 ‰ and -30 ‰, while C4 plants (grasses), characteristic of dry environments, produce organic matter with $\delta^{13}C$ between -10 ‰ and -15 ‰ (Meyers, 2003).

If the carbon source is predominantly algal, an isotopic change may reflect changes in the isotopic composition of the carbon source, the availability of CO_2 during photosynthesis of algae, and the composition of the phytoplankton community (Talbot et al., 2006). However, if the carbon source is mainly terrestrial, a negative change in the carbon isotope signature can indicate a change in vegetation from predominantly arid C4 pastures to a greater proportion of C3 vegetation and, therefore a more humid landscape (e.g. O'Leary, 1981). This proxy can be used in paleoclimatic studies to interpret changes in the primary productivity rate of the lake, as was done in Mono Lake (United States) (LRN 279), by Hodelka et al. (2020) to study paleoproduction and environmental changes, and also to identify the source of organic matter present in the lake, estimating the relative contribution of each source, as was done in Lago Castor (Chile) (LRN 377), by Fiers et al. (2019) to study the variability of the Chilean Patagonian hydroclimate.

3.2.2.2. Nitrogen Isotope ($\delta^{15}N$)

Isotopic nitrogen ($\delta^{15}N$) composition of lake sediments has been used in paleoenvironmental studies with a wide range of applications (e.g. Gayantha et al., 2017; Hodelka et al. 2020). This proxy can be used to identify sources of organic matter and nutrients in the lakes and to reconstruct their trophic status (Gayantha et al., 2017; Hodell and Schelske, 1998; Leng and Marshall, 2004; Meyers, 1997, 2003; Müller and Voss, 1999; Ogrinc et al., 2005; Talbot, 2001), in addition to provide information on changes in river basins that affect the N cycle of the lakes (Talbot, 2001).

However, although investigations with nitrogen isotopes are a powerful tool in their own right, interpretations of sedimentary $\delta^{15}N$ are quite difficult (Brenner et al., 1999; Meyers, 1997; Meyers and Teranes, 2001), since multiple factors may ultimately control the $\delta^{15}N$ of sedimented organic matter (Meyers and Teranes, 2001), which make them most effective when performed as part of a multiproxy study (Talbot, 2001).

We have identified high and low δ15N as environmental proxies in lake sediments, with main indicators/uses associated environmental interpretations summarized in Table 8 (Appendix I). $\delta^{15}N$ in organic matter is generally expressed in relation to the air standard (Viana et al., 2014). $\delta^{15}N$ is close to 0 ‰ for atmospheric N2 and 7-10 ‰ for dissolved inorganic nitrogen (DIN) (Meyers, 1997, 2003; Peters et al., 1978). Thus, phytoplankton using DIN have δ15N values around 8 ‰ and terrestrial plants using atmospheric N2 fixed by soil N fixers have values around 0-2 ‰ (Talbot and Lærdal, 2000).

High values of nitrogen isotopes may indicate higher rates of primary production (Talbot and Johannessen, 1992) and more contribution of phytoplankton that would correspond to an increase in the lake level (Viana et al., 2014), which may indicate wet periods. On the other hand, low values of nitrogen isotopes can indicate more contribution of atmospheric nitrogen to the lake (Olsen et al., 2013), column stratification and limited vertical DIN cycling (Hodelka et al., 2020) that would correspond to a decrease in lake level, which may indicate dry periods.

This proxy can be used in paleoclimatic studies to track changes in the source and paleoproductivity rates, as was done at Lake Bolgoda (Sri Lanka) (LRN 83), by Gayantha et al. (2017) to reconstruct the climatic evolution of the late Holocene in Sri Lanka, and also to define changes in the quantity and source of organic matter transported to the lake, as was done in Solniki palaeolake (Poland) (LRN 222), by Mirosław-Grabowska et al. (2015) to study the reaction of the lake environment to climate cooling.

3.2.2.3. Oxygen Isotope ($\delta^{18}O$)

Isotopic oxygen ($\delta^{18}O$) composition of either biogenic (skeletal), or authigenic (endogenic) mineral that precipitates in lake sediments can be used in paleoclimatic studies (Leng and Marshall, 2004). This proxy has been used to infer changes in the lake's water balance (e.g. Henderson et al., 2003; Horton et al., 2016; Leng and Marshall, 2004; Lister et al., 1991; Qiang et al., 2005; van Hardenbroek et al., 2018; Yuan et al., 2006), salinity (e.g. Liu et al., 2009a), evaporation and precipitation (e.g. Liu et al., 2009a; Zachos et al., 1994), and temperature (e.g. Xu et al., 2006, 2014). In general, the $\delta^{18}O$ values of autogenous lake carbonates are controlled mainly by the isotopic composition of the water at the time the carbonates precipitate in the lake, with secondary modification by temperature (O'Neil et al., 1969).

We have identified high and low δ^{18}O values as environmental proxies in lake sediments, and their environmental interpretation are summarized in Table 9 (Appendix I). These are generalized interpretations, and exceptions can be readily found. High oxygen isotope values may indicate more evaporation, considering that the water containing the lighter oxygen isotope ^{16}O is preferably lost during evaporation, leaving the lake water enriched in ^{18}O (Díaz et al., 2017; Li et al., 2016; Litt et al., 2009). Thus, high δ^{18}O values may indicate reduced precipitation (Li et al., 2016; Zachos et al., 1994) and warmer periods (Lauterbach et al., 2011).

This proxy can be used in paleoclimatic studies to understand the dynamics of the regional/local moisture source and / or precipitation, as was done in Lake Chenghai (China) (LRN 84), by Sun et al. (2019) to analyze changes in Indian summer monsoon strength during the last deglaciation and early Holocene, and also to study lake level variability, as was done in Lake Son Kol (Kyrgyzstan) (LRN 98), by Schwarz et al. (2017) to infer climate-driven regime shifts during Mid- to late Holocene in Central Tian Shan, Kyrgyzstan.

3.2.3. Physicochemical

3.2.3.1. Elemental Analysis and Inorganic Ratios

The development of X-ray fluorescence (XRF) core scanning technologies since the 1990s has enabled rapid, non-destructive, and high-resolution geochemical analysis of sediment cores (Croudance and Rothwell, 2015). Such micro-XRF core scanning has successfully been applied to lacustrine sediment sequences to reconstruct different climatic parameters such as variations in sedimentary inputs (Elbert et al., 2013; Kylander et al., 2011, 2012; Speranza et al., 2019), palaeoflood events (Moreno et al., 2008; Wilhelm et al., 2013), and aeolian inputs (Bakke et al., 2009).

In paleoclimatic studies, elementary data allow the reconstruction of changes in the hydrological regime of the water basin, expressed by changes in sedimentary inputs, in grain size, and in lake levels (Kylander et al., 2011). In this context, the main interest is to identify changes in the relative quantity of elements and in the nature of the material derived from the lake basin (Croudance and Rothwell, 2015). XRF scanners are fairly insensitive to organic matter, and when there is an increase in the levels of organic matter present in the sediments there is a dilution of the mineral components that can be measured. As lake sediments vary widely in the amount of organic matter, the variations measured in an element will largely reflect changes in organic material (Löwemark et al., 2011). Therefore, using this approach, it is necessary to normalize the elements, and this is done through the use of elementary ratios. The use of ratios can help to clarify the key processes governing downcore variations (Croudance and Rothwell, 2015).

We have identified 50 elements and ratios most applied in paleoclimatic reconstructions from lake sediments, these elements and ratios and their main indicator/use are summarized in Table 10 (Appendix I). Their associated environmental interpretations and example locations are presented in Table 11 (Appendix I). The interpretations presented should not be applied equally in all cases, as several elements play multiple roles depending on their individual chemistry and on varying lake conditions (Kylander et al., 2011). Lake characteristics, e.g., type, shape, geomorphological context and formation, geology and soils composition of the watershed should be considered to ascertain the most appropriate elements and ratios to focus on and underpin the paleoenvironmental interpretations for any given lake basin (Croudance and Rothwell, 2015).

Some lithogenic elements as Aluminium (Al), Iron (Fe), Potassium (K), Rubidium (Rb), Silicon (Si), Titanium (Ti) and Zirconium (Zr) are an indicator of detrital inputs because they are geochemically stable, hosted by resistant minerals, and conservative in most geochemical surficial environments (Boës et al., 2011). Similarly, some ratios as Al/Ca, Ca/Fe, Fe/K, Ti/Ca can also be used as indicators of detrital inputs (e.g. Elbert et al., 2013; Litt et al., 2009; Metcalfe et al., 2014; Tardy et al., 2004). Changes in grain-size of allochthonous material found in lake sediments have been inferred from elemental ratios such as Al/Si, Fe/Ti, Ti/K, Zr/Fe, Zr/K and Zr/Rb (e.g. Clift et al., 2014; Cuven et al., 2011; Kylander et al., 2011; Marshall et al., 2011; Wilhelm et al., 2013). Weathering and erosion processes can be identified by Ca/Al, Ca/Ti, K/Al, K/Ti, Niobium (Nb)/Ti, Rb/K and Rb/Strontium (Sr) (e.g. Fernandez et al., 2013; López et al., 2006; Olsen et al., 2013; Shala et al., 2014). Sr/Rb identities unweathered terrestrial fractions (Fedotov et al., 2012).

The presence of Ca and Sr is commonly associated with authigenic carbonate minerals or biogenic calcium carbonates in arid and limestone/carbonate environments, but can be covariant with lithogenic elements in volcanic or glacial environments, for example (Croudance and Rothwell, 2015). Ratios as Ca/Si, Ca/ΣTi, Fe, Al, Magnesium (Mg)/Ca and Sr/Ca are indicative of authigenic precipitation (e.g. Jouve et al., 2013; Martin-Puertas et al., 2011; Mueller et al., 2009; Wünnemann et al., 2010). Mg has been used as an indicator of detrital dolomite from outside the lake, and Ca/Mg is an indicator of biogenic calcite precipitation (Lauterbach et al., 2011). Si/Ti and Si/Zr have been used to estimate biogenic silica (e.g. Cuven et al., 2011; Stansell et al., 2010). Sr/Ti indicates $SrCO_3$ precipitation (Kylander et al., 2011).

Bromine (Br) forms strong covalent bonds with organic molecules (Gilfedder et al., 2011), therefore this element has been used to identify changes in organic content in lake sediments (Kalugin et al., 2013), in the same way as S/Ti (Moreno et al., 2007). Phosphorus (P) has been used to detect nutrient enrichment in the lake (Corella et al., 2012). Sulfur (S) is used to identify marine influence, leaching and evaporative concentration (Burn and Palmer, 2014). Thorium (Th) has been used to identify leaching during the defrost of permafrost (Fedotov et al., 2012). Fe/Si and Zr/Ti have been used as proxy of volcanic sediments (e.g. Brown et al., 2007; Van Daele et al., 2014). In a reducing environment, mainly associated to early diagenesis processes in sediments, the solubility of Fe and Manganese (Mn) increases, but Mn is more readily affected (Boyle, 2002), so redox conditions can be identified by the ratios Fe/Mn, Fe/Al, Mn/Fe and Mn/Ti (e.g. Corella et al., 2012; López et al., 2006). Lead (Pb) and Copper (Cu)/Rb can be used as an indicator of pollution from mining activity (Guyard et al., 2007).

Usually, several elemental analysis and inorganic ratios are used in paleoclimatic studies to do high-resolution geochemical profiles of the lake sediments, as was done in Les Echets (France) by Kylander et al. (2011), who analyzed the variation in the association of the studied elements (Ti, Rb, K, Zr, Si, Ca, Sr, Mn and Fe) with time and with changes in the lake, driven by changes in climate, in addition to used elementary ratios (Ca / Ti, Mn / Ti, Si / Ti, Sr / Ti and Zr / Rb) to complement the analysis of the lake's sedimentary sequence. This type of proxy has also been used in paleoclimatic studies with approaches that are not only qualitative but also quantitative, with the use of statistical methods, how was it done in Laguna Yema (Argentina) (LRN 391) by Speranza et al. (2019), who used Redundancy Analysis (RDA) and Principal Component Analysis (PCA) on the elements found to identify the possible mineralogical origins and the main sedimentary processes of particle entry, distribution and sedimentation in the lake. In association with pollen analysis and ^{14}C dating, this proxy was used to carry out a paleoenvironmental reconstruction of the semi-arid region of the Argentine Chaco.

3.2.3.2. Environmental Magnetism

Environmental magnetism is a systematic study about the magnetic properties of soil and sediment samples (Gayantha et al., 2017), and their connections with the environmental processes (Bali et al., 2017). Environmental changes, including climatic ones, which occur at different time scales, can influence production, transport, deposition, and diagenetic reactions of magnetic minerals in different depositional basins (Gayantha et al., 2017; Liu et al., 2012). These minerals, are sensitive to changes in environmental conditions, are quite often present in both sediments and soils (Evans and Heller, 2003). The size, shape and concentration of these minerals influence the magnetic parameters of sediments and their environmental interpretation (Bali et al., 2017; Gayantha et al., 2017). The techniques used in recent sediments studies have the advantage of being fast, sensitive and non-destructive (Bali et al., 2017; Gayantha et al., 2017). We have identified 13 magnetic parameters most commonly applied in paleoclimatic reconstructions in lake sediments, and they delivery ratios. These parameters and their basic interpretations are presented in Table 12 (Appendix I).

Magnetic susceptibility (χ) gives practical insights into distinguishing temporal and spatial changes in mineral composition, grain size distribution, and the abundance of magnetic minerals (Kılıç et al., 2018). In this way, it provides a useful proxy of changes in the relative intensity of terrigenous input into the lake (Eriş et al., 2018). Low and high frequency magnetic susceptibility (χlf and χhf) can indicate the type and concentration of the magnetic minerals in the sample (Mehrotra et al., 2019). The relative frequency-dependent magnetic susceptibility (χfd%) [(χlf - χhf)/ χlf x 100] is considered to record the superparamagnetic (SP) ultrafine (~0.02 µm) ferrimagnetic minerals (e.g., magnetite) during soil formation (Daering, 1999a; Dearing et al., 1996; Thompson and Oldfield, 1986).

The anhysteretic remanent magnetization (ARM) is normally used to analyze some parameters as anhysteretic susceptibility (χARM) and some inter-parametric ratios. ARM/SIRM and ARM/χ can indicate magnetic minerals type and size (Hunt et al., 1995). The χARM approximates the concentration of remanence carriers, predominantly the single domain (SD) and fine pseudo single domain (PSD) particles of the ferrimagnetic minerals (King et al., 1982). The inter-parametric ratios χARM/χlf and χARM/SIRM are used to determine the magnetic grain size (Oldfield, 1991).

The Isothermal remnant magnetization (IRM) is normally used to analyze some parameters as soft isothermal remanent magnetization (SIRM), hard isothermal remnant magnetization (HIRM) and other inter-parametric ratios (Bali et al., 2017). SIRM, as well as χ, is mainly sensitive to the magnetic minerals' concentration. However, SIRM is more strongly affected by the magnetic grain size and by any antiferromagnetic minerals and is unaffected by paramagnetic components (Sandgren and Thompson, 1990). HIRM [(SIRM+IRM$_{-300mT}$)/2], can be used to quantify the absolute concentration of high-coercivity components (Thompson and Oldfield, 1986). The inter-parametric ratio SIRM/χ_{lf} can be used to support the existence of authigenic magnetite (Wei et al., 2018). The S-Ratio (IRM$_{-300mT}$/SIRM) is used to estimate the relative contributions of the ferrimagnetic (e.g., magnetite and/or maghemite) and anti-ferromagnetic minerals (e.g., hematite and/or goethite) (Evans andHeller, 2003; Walden et al., 1999).

This proxy can be used in paleoclimatic studies to identify variations in precipitation (χlf, χfd, χARM, SIRM), in association with the granulometry of magnetic minerals, as was done at Shantisagara Lake (India) (LRN 116), by Sandeep et al. (2017) to study the variability of the Indian monsoon during the Holocene in India, and also to evaluate the entry of debris into the lake through the variation of magnetic particles in the sediments, as was done in Lake Acigol (Anatolia) (LRN 79), by Demory et al. (2020) to study chronostratigraphy, depositional patterns and climate impressions in the lake region during the Quaternary.

3.2.3.3. Grain Size Analyzes

Grain size is the most fundamental physical property of the sediment (Bali et al., 2017). Its analysis allows the understanding of transport energy and depositional environment (e.g. Basavaiah et al., 2014; Cuven et al., 2010; Gayantha et al., 2017; Sly, 1978), level of the lake (e.g. Reineck and Singh, 1980) and provenance of the sediments (e.g. Conroy et al., 2008). As climate variability influences these parameters, the granulometric analysis of a sediment profile provides useful information on the dynamics of the sedimentary environment (Singh and Singh, 2005) and, consequently, on the climatic conditions at the time of sediment deposition (Bali et al., 2017). We have identified three classifications based on grain sizes and their environmental interpretation associated, which are summarized in Table 13 (Appendix I).

Rainfall plays a crucial role in transporting and depositing sediment from the river basin to the lake basin (Sandeep et al., 2017). During periods of high (low) precipitation, a large (small) proportion of coarse sediments is transported to the center of the lake due to higher (lower) energy of the means of transport (Anoop et al., 2013a; Chen et al., 2004; Conroy et al., 2008; Gayantha et al., 2017; Peng et al., 2005; Sandeep et al., 2017). Variations in particle sizes can indicate alternation between high to intermediate/low lake levels (Guerra et al., 2017). In addition, factors such as anthropogenic erosion, morphological changes in the watershed, the hydrological budget of the watershed, the lake itself, and the vegetation around the lake can influence variations in grain size of lake sediments (Babeesh et al., 2019; Bhattacharya and Byrne, 2016; Gayantha et al., 2017; Issaka and Ashraf, 2017).

This proxy can be used in paleoclimatic studies to investigate the energy and mode of transport in the lake basin and the shoreline proximity. For example, in Ennamangalam Lake (India) (LRN 73), Mishra et al. (2019) assessed the changes in monsoon system during the late Holocene in India, and also to identified changes in the lake's energy and, consequently, the deposition environment. This approach has also been successfully applied in Manasbal Lake (India) (LRN 107), by Babeesh et al. (2019) to study paleoenvironmental changes during the late Holocene in India.

4. Discussion

4.1. Interpretation of proxies

Lake sediments can be used to reconstruct high temporal resolution of past climate (e.g. precipitation and temperature), land management, and environmental or limnological conditions of the lake (Speranza et al., 2019). In paleoclimatic and paleoenvironmental studies carried out in lake sediments, each proxy reflects the environment by its own spatial scale, occupying a unique place in the lake's ecosystem network, and providing information on different facets of that ecosystem (Birks and Birks, 2006). Despite this, as the sedimentary and biogeochemical processes differ between the lakes, the results and interpretations obtained for a given proxy in a given lake may not be directly applicable to other lakes (Vegas-Vilarrúbia et al., 2019). The interpretation of results obtained must be done sparingly, since the interpretation based on exclusive parameters or proxies may not only be misleading but may also not address the genetic complexity of the lake environment (Nowacki et al., 2019).

An example is that in a study by Elbert et al. (2013), carried out in Laguna Escondida (LRN 385) and Lago Castor (LRN 377) (Chile), the element calcium (Ca) was interpreted as an indicator of allochthonous lithoclastic material in the lakes (mainly tephra plagioclase and eroded soils) (Figure 12.A). The catchment area of these lakes is mainly composed of Cretaceous volcanic rocks (Elbert et al., 2013), with the basin soils classified as humic umbrisols (Dijkshoorn et al., 2005). In addition, these lakes are in the Volcanic Zone of Southern Chile (Parada et al., 2001) that was covered by ice during the Last Glacial Maximum (Glasser et al., 2008), and presents mostly areas of glacially scoured bedrock, where lakes are located along fault lines (Glasser et al., 2009). However, in a study done in Lake Tana (Ethiopia) (LRN 33), Ca was interpreted as an indicator of autochthonous material in the lake by Marshall et al. (2011) since the surface catchment of the lake is dominated by Quaternary basic igneous lithologies which enclose a variety of xenoliths that span in composition from peridotite through pyroxene, and gabbro to alkali granite (Ayalew et al., 2003). The increase in Ca indicates a decrease in the input of allochthonous elements (Marshall et al., 2011) and an increase in the elements present in the basement rocks of the lake (Figure 12.B). Through these examples, it is possible to see that the same proxy, in this case, Ca can be interpreted differently according to the local context and the particularities of each lake.

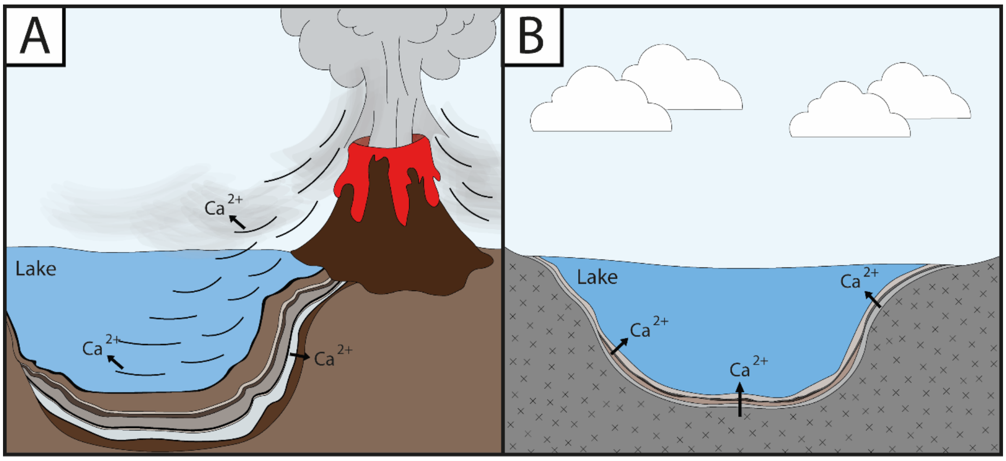

Figure 12. Comparative chart of Ca proxy at different scenarios A) Lake in a volcanic context, like Laguna Escondida and Lago Castor (Elbert et al., 2013), where high Ca values were identified in the tephra deposits, indicating the entry of allochthonous material in the lakes. B) Lake with a basement composed by Quaternary basic igneous lithologies, like Lake Tana (Marshall et al., 2011), where high Ca values indicate a

decrease in the input of allochthonous elements and an increase in the elements present in the basement rocks of the lake.

Reconstructions and derived inferences for any proxy require a complete understanding of the spatial and temporal framework in which the environmental processes and conditions that lead to the existence and persistence of each specific proxy are coherent (Vegas-Vilarrúbia et al., 2019). When the general framework in which the lake is located or the limitations of each proxy are not considered, contradictory interpretations can be made. Therofore, the context of the lake must be considered, since the aspects of the environment the proxies are inserted interfere how to interpret them, as well as information on the appropriate use of calibration data and existing limitations (Bigler et al., 2002; Rosén et al., 2003).

This situation occurred in studies carried out in Lake Boqueirão (Brazil) (LRN 392). Zocatelli et al. (2012) adopted different parameters of organic matter (e.g. TOC) and ^{14}C dating to study paleoenvironmental changes in northeastern Brazil such as to reconstruct the variations in the level of Lake Boqueirão during the late Holocene. Gomes et al. (2014) presented an evaluation of a transfer function based on diatoms developed to reconstruct the depth of this lake. Viana et al. (2014) used the same transfer function based on diatoms, associated with different parameters of organic matter (e.g. TOC, C / N), carbon and nitrogen isotopes, grain size analysis and ^{14}C dating to reconstruct lake level fluctuations and environmental changes during the late Holocene. In these studies, the interpretation of the results found for the reconstruction of the lake level was very similar, with the association of the increase in the lake water level with more humid periods, with greater precipitation. Zular et al. (2018) used the same proxies as Viana et al. (2014), but instead of ^{14}C, optically stimulated luminescence (OSL) dating was performed to study the dynamics in the formation of dune-dammed lakes in northeastern Brazil during the Mid-Holocene. This study considered changes in the wind variable for the first time to assess paleoclimatic and paleoenvironmental reconstructions. Unlike previous studies, the results obtained in this study indicated an increase in water levels in Lake Boqueirão during periods when drier climatic conditions prevailed. Furthermore, Zular et al. (2018) suggest that in paleoenvironmental investigations and geomorphological evolutions, river or wind processes should be examined together. In this way, it is possible to understand the general environmental picture of the lake's formation, allowing a more robust reconstruction. More recently, to study the Tropical

South Atlantic influence on Northeastern Brazil precipitation, Utida et al. (2019) used the core Boqc09 / 01 from Viana et al. (2014) and their dating to obtain a high-resolution record of the isotopic hydrogen composition of the n-C28 alkanoic acid (δDwax) from that core. The results obtained in this study were compared with the results obtained in previous studies, showing a great similarity between the record obtained in this work, by δDwax, and the lake level variations reconstructed based on a diatom transfer function of the same core by Viana et al. (2014). However, this comparison showed an inconsistency: the periods with an increase (decrease) in precipitation indicated by lower (higher) values of δDwax obtained in this study, occur during periods of significant fall (increase) in the lake level reconstructed by Viana et al. (2014) and Zocatelli et al. (2012). According to Utida et al. (2019), this divergence may have occurred because these previous works did not consider that Lake Boqueirão is a coastal lake that originated from a small freshwater river and occurs between sand dunes, and consequently the level of water was strongly influenced by the wind processes. Based on isotopes data obtained in this study, they also suggested that increase in the level of the lake is related to the advances of the dunes over drainage in dry periods, as well as decrease in the level of the lake is related to the increase in the drainage flow in wetter periods. Once again, a complete view of the context and characteristics of the studied lake is mandatory to do not misinterpret results.

For a correct interpretation of the results, it is also necessary to have good incorporation of the data, which often depends on numerical techniques for summarizing large amounts of data (Birks, 1998; Bradshaw et al., 2005a). In any paleoclimate reconstruction, a reliable chronology is fundamental (De Batist et al., 2008), as well as avoiding the “Reinforcement syndrome” (Watkins, 1971; Thompson and Berglund, 1976; Bennett, 2002). This syndrome is a confirmatory approach where there is a tendency to try to combine small changes in the data set to adjust or confirm a current paradigm or model and ignore other changes and, to avoid that, it is important to let the data speak for itself (Birks and Birks, 2006).

In conclusion, for the results obtained through the study of different proxies to be more securely interpreted, the entire spatial and temporal structure of the lake must be considered, taking into account the climatic (macro and micro climate) and environmental (geology) context, geomorphology and vegetation), the processes that act in the hydrographic basin and in the lakes (the type of system and catchment area) and that contribute to their formation and alteration, and the influence of anthropic actions (land cover and use), avoiding misinterpretations and respecting the particularities of each lake. In addition, techniques and methodologies must be used to allow more efficient data analysis, i.e., a robust age model, an appropriate choice of sampling location, and the interpret results based on data alone, not on personal judgments and preexisting concepts.

4.2. Evolution of proxy use over time

Multiproxy studies can provide complementary information about the paleoenvironment by combining different independent proxies (Ficken et al., 2002). Considering the three types of proxy analyzed in the present study, biological, isotopic ratio and physicochemical, we observed an evolution in the use of these types of proxy in the analyzed studies, in the period from 1985 to 2020, as shown in Figure 13.

In the 1980s, almost all studies used only biological proxies. From the 1990s, isotopic ratio started to be used with more frequency and, at the end of this decade, the physicochemical proxies began to be used. From the 2000s on, the increase in the use of physicochemical proxies is constant, while biological ones continued to be the most used type and isotopic ratio remained commonly used, only less frequently compared to the other two types of proxy.

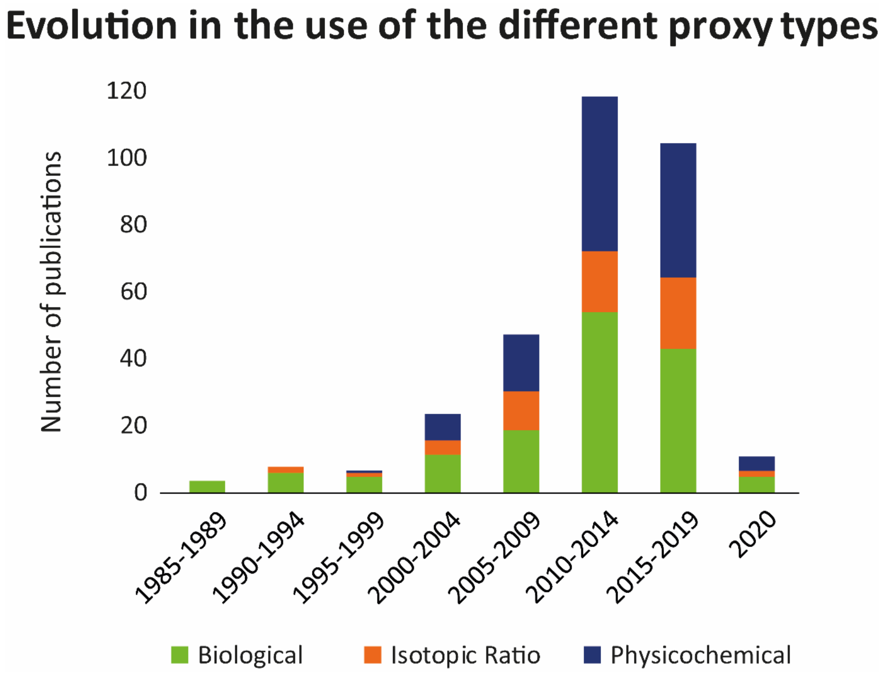

Figure 13. Evolution in the frequency of the three types of proxy for the publications considered in this study, from 1985 to 2020.

Figure 14 shows the frequency of use for each type of proxy in the last 35 years (1985-2020). Among biological proxies, organic matter is the proxy that has been most frequently used, followed by pollen analysis and diatom analysis. Among the isotopic ratios, carbon isotopes ($\delta^{13}C$) have been more frequently used, followed by oxygen ($\delta^{18}O$) and nitrogen isotopes ($\delta^{15}N$). Amid physical-chemical proxies, elemental analysis and inorganic ratios have been more frequently used, followed by environmental magnetism and grain size analysis.

Figure 13 and Figure 14 show that paleoenvironmental and paleoclimatic studies using lake sediments have moved from an initially predominantly biological approach to approaches using more than one type of proxy, what has been most common. With the development of new techniques and the discovery of new proxies, new studies have been carried out, often in lakes previously studied, generating new results and new interpretations. This is the case with Lakes Qinghai, Tanganyika and Laguna La Gaiba, that have been the subjects of several studies in recent years, using different proxies and techniques, according to the objective of each study.

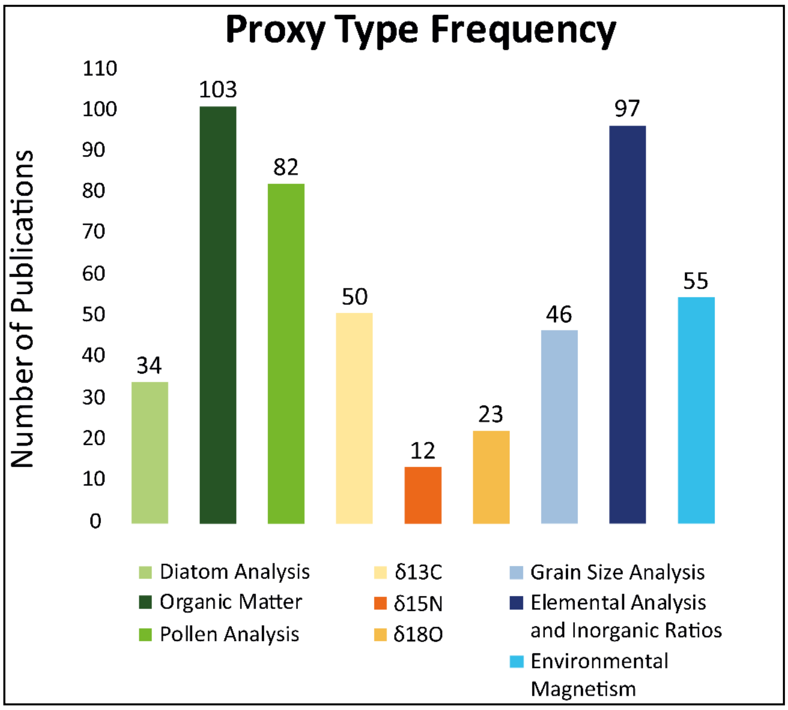

Figure 14. Frequency with which each proxy analyzed in this study has been used in the considered period, between 1985 and 2020.

Lake Qinghai (LRN 96), in China, was studied by Lister et al. (1991) using oxygen isotopes to identify isotopic changes in lake water that could indicate changes in climatic conditions, especially related to the Asian monsoon since the latest Pleistocene. Henderson et al. (2003) used carbon and oxygen isotopes and grain size analysis to infer past lake level and, indirectly, effective moisture with a record of very recent climate change, i.e. less than 150 years. Shen et al. (2005) used a multi-proxy analysis with organic matter, pollen analysis and carbon isotopes to obtain the high-resolution climatic evolution of the lake since the Last Glacial. Xu et al. (2006) used a multi-proxy approach, with carbon, nitrogen and oxygen isotopes and organic matter to understand the climate implications of different proxy indices and how they are related. Liu et al. (2007) and Liu et al. (2009a) used oxygen isotopes as indicative of monsoon system changes. And, more recently, Horton et al. (2016) used data from Xu et al. (2006) in a compilation, in which carbon and oxygen isotope data were reviewed and analyzed to identify variations in the hydrological balance of several lakes.

Lake Tanganyika (LRN 56), in East Africa, was studied by Jolly et al. (1998), through a comparasion of pollen data with climate and vegetation model simulations to translate climate variables into estimates of potential vegetation for the last glacial maximum (LGM) and early mid-Holocene. Alin and Cohen (2003) used grain size analysis to infer water-depth reconstruction and recreate lake-level history for the past 2500 years. Burnett et al. (2011) used a multiproxy approach with organic matter, carbon isotopes, elemental analysis and inorganic ratios to understand the timing and mechanisms behind East African climate change over the past 90 kyr, and its relation to global climate.

Laguna La Gaiba (LRN 387), in Bolivia, was studied by Whitney et al. (2011) using pollen and diatom analysis and environmental magnetism to obtain a high-resolution, well-dated ~45 kyr climate record from this lake. Metcalfe et al. (2014) used pollen and diatom analysis, and environmental magnetism, as well, but also carbon isotopes, elemental analysis and inorganic rations in a more complete approach to identifying records of environmental changes in this lake over the last 25000 years.

These examples allow us to observe the evolution of the types of proxy used in the different paleoclimatic and paleoenvironmental studies in lakes in different regions of the planet, going from studies with only one proxy to multiproxy studies, over the years.

Another essencial aspect of lake sediments studies identified by the present review is a discrepancy both in the density and in the quality of paleoclimatic and paleoenvironmental studies carried out in lakes in the Northern and Southern Hemispheres, during the last 35 years. In the Northern Hemisphere, more studies have been published. Additionally, they are more comprehensive such as the use of various proxies, data with higher resolution, and more datings, when compared to the studies carried out in the Southern Hemisphere. This discrepancy possibly occurs because most of the least developed countries are in the Southern Hemisphere, which has limited progress in information, which can be correlated with the socio-economic development of these countries (Lau, 2006). In addition, the conditions of access to the lakes, such as vegetation, relief and human occupation, can also influence the study of the lakes (e.g. Garnier et al., 2020).

Moreover, accurate dating is essential in paleoclimatic studies, since the degree of success in discerning patterns of climate and environmental change depends on the level of correlation of paleorecords, which is related to the quality of the age model (Zimmerman and Wahl, 2020). Reliable estimates of the age of past events are fundamental, because without them it is impossible to investigate whether they occurred at the same time, whether certain events led or delayed others, and it is impossible to accurately assess the rate at which the past environmental changes occurred (Bradley, 1999). Besides that, without a robust age model, the interpretation of the results of different proxies may appear to have a temporal relationship, when in fact they may be separated by several centuries (Zimmerman and Wahl, 2020).

A reliable chronology for lake sediment studies is usually provided both by the appropriate choice of sampling sites and by high-resolution radiocarbon dating, usually, AMS ^{14}C, where dates need to be calibrated in calendar years to provide a linear age scale on which other chronologies (e.g. ^{210}Pb, ^{137}Cs) can be combined (Birks and Birks, 2006). The limiting factor of any age model is the number and reliability of the available radiocarbon or other types of dates (Telford et al., 2004b).

Lake Ohrid (LRN 189), in Albania and Macedonia, has a large number of independent stratigraphical markers (e.g. tephra layers) that, in combination with the lithological and sedimentological peculiarities, makes Lake Ohrid a valuable archive for palaeoenvironmental and paleoclimatological studies (Vogel et al., 2010). This lake has been the subject of many studies in the last decade, using different proxies and techniques, according to the objective of each study. Vogel et al. (2010) used ^{14}C dating and tephrostratigraphy to establish an age model, in addition to elemental analysis and inorganic ratios, environmental magnetism and grain size analysis, to study the dispersion of tephra originating from explosive eruptions of Italian volcanoes during the Quaternary. Sadori et al. (2016) used ^{14}C dating and tephrostratigraphy to establish an age model, and organic matter and pollen analysis to have a better understanding of the paleoclimatic and paleoenvironmental evolution of the lake.

Kousis et al. (2018) used tephrostratigraphy to support their chronology, based on orbital tuning, in addition to pollen analysis, to study the vegetation dynamics and climate variability in SE Europe. Panagiotopoulos et al. (2020) used tephrostratigraphy and orbital tuning to establish an age model for Lake Ohrid (LRN 189), and pollen analysis complemented by organic matter and diatom analysis, carbon and oxygen isotopes, elemental analysis and inorganic ratios and grain size analysis to identify ecosystem and vegetation changes in southern European during the Early Pleistocene. In conclusion, in some case such as Lake Ohrid, coupling dating techniques (e.g. ^{14}C) with regional events by tephra layers and different types of proxy led to obtain a more robust age models.

In the context of evolution of the use of different types of proxy over time, our compilation revealed an evolution of basically biological approaches that, over the years, have become predominantly multiproxy. It was also possible to observe the development of new proxies and new techniques to meet the needs that arose along time, evolving differently in the Northern and Southern Hemispheres. In addition, it was noted the improvement of chronological tools, including improvement in ^{14}C dating, the inclusion of new dating methods (e.g. ^{210}Pb, ^{137}Cs), and the association of different methods to obtain more complete age models.

4.3. Advantages of multiproxy approaches

Ecosystems are formed by a complex network of biochemical interactions, making it interesting to study the largest number of possible proxies (multiproxy approach) for a broader view of their context than could be acquired from a single proxy (Smol, 2002; NRC, 2005). The multiproxy approach has recently become a common approach in paleolimnological, paleoecological, and sedimentological research to reconstruct the paleoenvironment (Nowacki et al., 2019).

Different proxies reflect different environmental and climate factors, providing evidence for the same processes or cascades of processes (Nowacki et al., 2019), in addition to operating at different spatial and temporal scales (Birks and Birks, 2006; Nowacki et al., 2019). Therefore, the choice and use of each proxy requires prior assessment, considering the entire environmental context, in addition to the pros and cons associated with each proxy (Nowacki et al., 2019).

Castro et al. (2019) used a multi-proxy analysis of biological (organic matter and pollen) and physical-chemical indicators (environmental magnetism and grain size analysis) from sediments from Lake Pastahué (LRN 398), in Chile, to determine the environmental response to events climate and anthropogenic activities in the last 1000 years. Panagiotopoulos et al. (2020) used the multi-proxy approach and integrated data from biological proxies (diatoms, organic matter and pollen), isotopic ratios (carbon and oxygen isotopes) and physicochemical proxies (environmental analysis and isotopic ratios and grain size analysis) to restrict the influence of local factors to responses of the aquatic and terrestrial ecosystem to climatic variability around Lake Ohrid (LRN 189).

Paleoenvironmental reconstructions using a single proxy are restricted by the limitations of that proxy (Ficken et al., 2002). In lake sediments, some biological proxies (e.g. diatoms, pollen) may have their preservation compromised in periods of prolonged drought, associated with a large decrease in lake levels and potential increase in of water salinity (Kiage and Liu, 2006). Other biological proxies as organic matter parameters (e.g. C/N) can be influenced by early diagenetic changes (Spiker and Hatcher, 1987), and by the variability in the composition of the organic matter source, which complicates and even obscures the identification of the diagenetic effects (Meyers et al., 1995). Isotopic ratios ($\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$) can be influenced by the physical processes and chemical degradation of the material that document the isotopic data in lake sediments, as well as the effects of equilibrium and/or rationing of the isotopes during the formation of that material (Bird et al., 2020).

Chemical records in lake sediments are the integrated result of a variety of factors and processes, including composition of source rocks, weathering uptake, atmospheric deposition, transport efficiency, sedimentation and post-depositional processes (Boyle, 2002). These processes can be affected by the past changes in climate, as well as by the general status of the lake (e.g. salinity, productivity, internal processes), and the duration of these events influences its recording, and so small-scale changes can be lost or its signals diluted by using traditional methods of subsampling and chemical analysis (Kylander et al., 2011). Magnetic minerals present in lake sediments can be derived from different sources (Walden et al., 1999), and can have a contribution from bacterial magnetite (Snowball, 1994), from authigenic greigite (Snowball, 1991), and from anthropogenic maganetite (Gautam et al., 2004). The magnetic dissolution due to the decomposition of organic matter can occur in theses magnetic minerals (Anderson and Rippey, 1988).

So even though multiproxy approaches are fraught with their own set of challenges and limitations (Bigler et al., 2002), the appropriate combination of proxies allows the complementary strengths of each proxy to be exploited, and the weaknesses to be identified (Mann, 2002). Thuerefore it is possible to increase the understanding of the system and improve the validation of the derived characteristics (Nowacki et al., 2019), avoiding ambiguities in the interpretation of the results. Besides that, the weaknesses evidenced by the multiproxy studies should not be ignored, as they can point out deficiencies and limitations in the methodology and in the proxies, and generate new questions that, to be resolved, promote new approaches and new techniques and stimulates new studies (Birks and Birks, 2006).

Sandeep et al. (2017) conducted a multiproxy approach to study paleomonsoon and vegetation of southern India during the Holocene. Through the association of biological proxies (C/N ratio, carbon isotopes), magnetic parameters, and granulometric analysis, the authors conducted a study to identify periods of high and low precipitation with less ambiguity, since the interpretations were made based on different results, and obtained important information for the reconstruction of the Indian Summer Monsoon (ISM) in the past.

Statistical techniques that consider the inherent properties of multiproxy data (Birks 1993b, 1996, 1998) can play a key role in testing hypotheses in paleoclimatic studies (NRC 2005). Principal Component Analysis (PCA) is a multivariate data analysis (Xue et al., 2011) commonly used to measure the relationship between two or more variables (Eladyady and Lotfy, 2016; Koinig et at., 2003; Pulice et al., 2013; Xue et al., 2011), and to group samples in large data sets (Xue et al., 2011). However, PCA is a semi-quantitative approach, that only groups the data but does not allow its quantification (Xue et al., 2011), and so must be used in association with other types of analysis such as pollen analysis and inorganic elements (e.g. Cassino et al., 2020).

More recently, PCA has been used in many related research fields, such as environmental forensics (Mudge, 2007), in the identification of crude oil samples (Peters et al., 2007), and in paleoenvironmental reconstruction from lake sediments. Gjerde et al. (2018) used the PCA to explore Lake Hakluytvatnet's (LRN 172) multi-proxy dataset, including variations in grain size distribution, as well as different geochemical elements.

Mehrotra et al. (2019) used a fossil pollen assembly PCA to study how relationships between variables and identify the main component that explains the greater variation of this proxy in the Lake Tso region (LRN 114). Speranza et al. (2019) used PCA to identify the main sedimentary processes that control the entry, distribution, and sedimentation of particles in the sediments at the bottom of Laguna Yema (LRN 391). Xiao et al. (2018) used PCA to study the sand fraction time series, the abundance of coastal ostracodes, percentage of pollen and the average annual precipitation at the Lake Hulun (LRN 75) in Asia. In all of these studies, PCA was used as a tool for paleoenvironmental reconstruction of the lakes' region.

No single proxy is adequate to reconstruct large-scale patterns from the past climate (Mann, 2002), and the multiproxy approach can provide more information about the climate system than the sum of the individual proxies since the interpretation based only on a parameter or proxy can be misleading and may not address all the complexity of the system (Nowacki et al., 2019). Besides that, well-designed multiproxy studies can provide potentially independent evidences that permit assessing competing hypotheses (Bennett and Willis, 2001), contributing to a better understanding of how lakes and their biota respond to internal and external events them, and the strengths and weaknesses of each proxy (Birks and Birks, 2006). This type of approach allows both the direct study of lake responses to climate change in the past and the testing of different hypotheses about lake development (Birks et al., 2010).

5. Conclusion

In this review, we examined the applications, limitations and other factors that influence the usage and interpretation of some of the major proxies used in the lake sediment studies. To achieve it, we considered 410 lakes distributed around the world studied by 195 publications. As a first consequence of our study, we highlight that the interpretation of the data obtained through these proxies should be done with caution since the same result can have different interpretations according to the environmental and climatic context of each lake. An evolution in the use of proxies was observed over time, moving from predominantly biological approaches to multiproxy, with the development of new techniques and methodologies, as statistical and numerical methods (i.e., PCA). The conditions of access to the lakes were iddentified as another aspect that can influence their study, taking as an example the lowest number of studies in lakes in regions of higher altitude (> 5000m). Regarding datings, the improvement of chronological tools with the association of different methods to obtain more complete age models was also noted. However, the evolution of those tools occurred differently in the Northern and Southern Hemispheres.

As changes in the environment affect different proxies in different ways, single proxy analysis is not suitable for long-scale paleoclimatic and paleoenvironmental reconstructions, as the results are restricted by the limitation of each proxy. On the other hand, the joint use of different types of proxy, resulting in a multiproxy approach compensates the limitations of individual proxies. Therefore, multiproxy studies can provide potential independent evidence that complements each other, or even reinforce a given hypothesis, contributing to more complete studies.

This review also led to the conclusion that the use of proxies in lake sediment studies for paleoclimatic and paleoenvironmental applications require: (1) a complete view of the context and characteristics of the lake/basin, taking into account the climatic (macro and micro-climate) and environmental (geology, pedology) context, geomorphology and vegetation), the processes that act in the hydrographic basin and in the lakes (the type of system and catchment area) and that contribute to their formation and alteration, and the influence of anthropic actions (land cover and use); (2) a robust and reliable age model; (3) the limitations of each proxy must be considered and, if possible, compensated with the use of another proxy; and (4) the interpretation of the results must be done based on data alone, not on personal judgments and preexisting concepts. We stress that the consideration of these factors and the database generated in our study can assist future researches, promoting more direct and robust studies.

6. Acknowledgements

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7. References

References to this article can be found in Appendix I.

3.2. ^{14}C Age Calibration

The results of this item compose the manuscript entitled *"A fully calibrated and updated Mid-Holocene Climate reconstruction for eastern South America"* from Gorenstein et al. that is in preparation. This study was developed in collaboration with a research group from the Instituto Oceanográfico da Universidade de São Paulo (IOUSP) and is part of the Master's Dissertation of the student Iuri Gorenstein.

The study by Gorenstein et al. used a different dataset from the one used in the previous article and aims to update the compilation made by Prado et al. (2013) with the addition of new records and with the calibration of the uncalibrated ^{14}C age models used in this article. Prado et al. (2013) made a compilation for eastern South America during Mid-Holocene by including more recent records and calibrating age models that were not previously calibrated. This update is necessary because since the work of Prado et al. (2013) recent work has been done with new paleorecords that should be added to this compilation to promote more robust climate reconstructions. In addition, the calibration of the age model of the paleorecord is necessary because it is one of the most important characteristics of a proxy analysis, since the uncertainties of the age of a sample are responsible for attributing or not a specific characteristic or climate change to a geological period (Lowe and Walker, 1997). Conventions for calibrating terrestrial samples from the SH have evolved over time and, since the last two decades, radiocarbon dating of any paleo record has become indispensable for a more accurate and reliable reconstruction of an earlier climate (Hogg et al., 2013).

My contribution to this study was the calibration of the considered ^{14}C age models for Mid-Holocene records using the same methods described in the item 2.4 of this Dissertation. These results regarding age model's calibration are described below.

3.2.1. Highlights

- 174 compiled paleorecords for South America during Mid-Holocene;
- Compiled data with age models calibrated, when they were not previously calibrated;
- 66 new calibrated age models.

3.2.2. Preliminary results

The formation of the ^{14}C radioisotope occurs in the upper troposphere and stratosphere (Törnqvist et al., 2015). When carbon is incorporated by an organism, radioactive decay is balanced by ^{14}C replacement due to photosynthesis in plants and the consumption of plant tissue by animals and the decay of the ^{14}C isotope begins after the death of the organism (Albarède, 2009; Ruddiman, 2008). Many mechanisms, such as the geomagnetic field strength, the solar activity, the increased burning of fossil fuels and the nuclear tests in the 1950s, causes changes in the production rate and / or exchange rate between carbon reservoirs, which culminates in variations in the content of ^{14}C in the atmosphere over time (van der Plicht, 2015). These variations affect radiocarbon dating and often limit the accuracy of age estimates (Hajdas, 2008).

The geomagnetic field strength and solar activity influence the production rate of cosmogenic isotopes and consequently, the production rate of atmospheric 14C. The increasing burning fossil fuels, in the late 1980s and early 1990s added a significant amountof ^{14}C free carbon dioxide to the atmosphere (Hajdas, 2008). The nuclear bomb tests almost doubled the amount of ^{14}C in the atmosphere in the 1950s, which reached maximum values in the mid-1960s (Manning et al. 1999). Since then, atmospheric ^{14}C has decreased, due to the absence of major atmospheric nuclear explosions, the continuous release of ^{14}C-free CO_2 to the atmosphere because of the combustion of fossil fuels and rapid exchanges between atmosphere, ocean and biosphere (Hua, 2009; Hua et al., 2013). Currently, the atmospheric ^{14}C is slightly higher than its pre-bomb value (e.g., 32.5 mean $\Delta^{14}C$ (‰) in 1957; 41.1 mean $\Delta^{14}C$ (‰) in 2011 in SH zone 3) (Hua et al., 2013). However, as most of these atmospheric nuclear tests were carried out in the NH, the spatial distribution of ^{14}C bombs during this period did not have a simple latitudinal gradient (Hua and Barbetti. 2007; Hua et al., 2013).

Hua and Barbetti (2004, 2007) demonstrated that $\Delta^{14}C$ levels in the troposphere during the initial pumping period were strongly influenced by atmospheric circulation. As a result, the spatial distribution of the ^{14}C bomb during this period did not have a simple latitudinal gradient, but consisted of 3 different zones in the NH and 1 zone for the entire SH (Figure 15) (Hua et a., 2013), which was also proven by Ancapichún et al. (2021). Therefore, radiocarbon ages require calibration to obtain calendar ages, since this calibration compensates for the error introduced by conventional half-life (Libby ages) and the temporal variability of the atmospheric ^{14}C content (Hajdas, 2008).

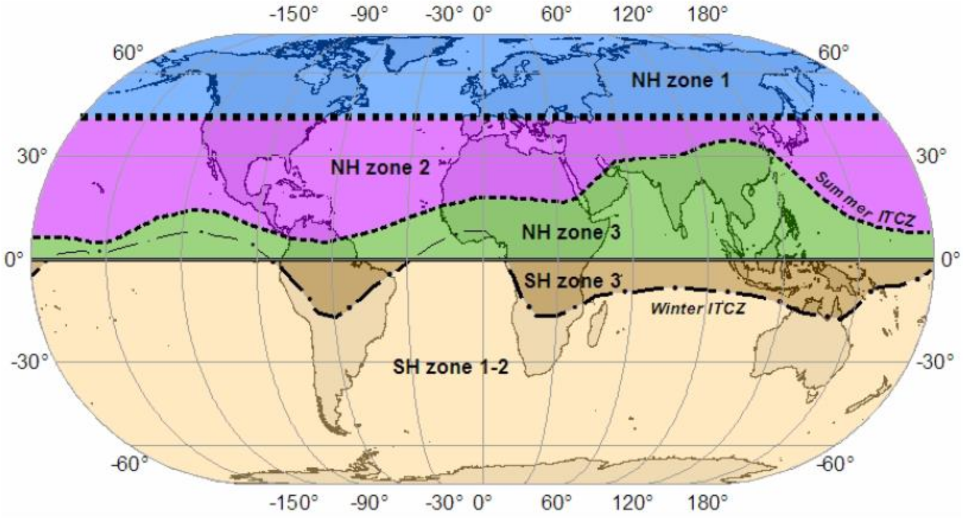

Figure 15. World map showing zonal atmospheric bomb 14C (Hua et al., 2013).

In Prado et al. (2013), 60 of the 120 paleoclimatic records had calibrated ages. We calibrated the ages of the remaining 60 records, and add 6 new records. Were calibrated dates from different paleoarchives: speleothems, marine, lacustrine and terrestrial cores and soil samples. All the records calibrated in this study are presented in Table 14 (Appendix II) and in

Figure 16.

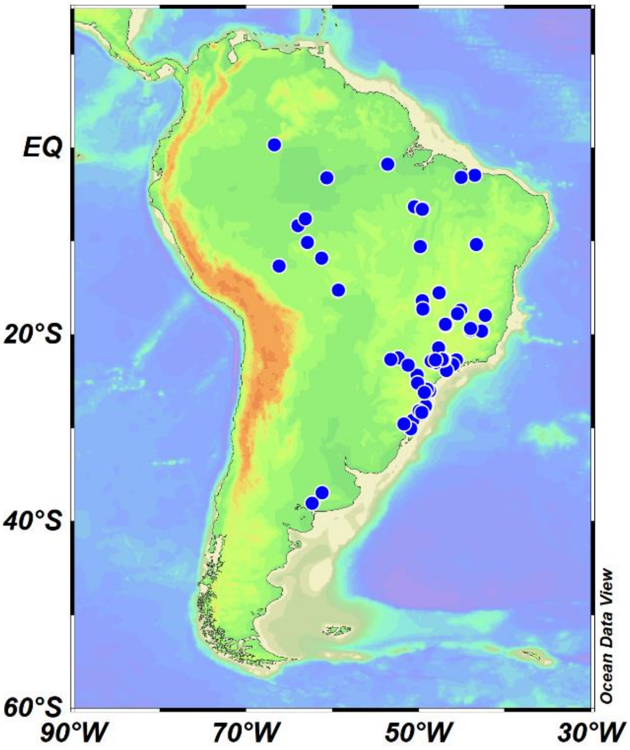

Figure 16. Map with the geographic distribution of the data sets considered (blue circles) for 14C age calibration.

The results obtained in the ^{14}C age calibration are available in Table S2. In the study by Gorenstein et al., the period defined as MH was considered from 7000 to 5000 years before present (yr BP) to assure the considered paleorecords emcompassed the MH period and consider uncertainties in the age models. Five from the 120 records compiled by Prado et al. (2013) could not be used in the updated compilation because after age model calibration the ages were out of the MH time interval defined in the Gorenstein et al.' study, as shown in Table 15 (Appendix II). We concluded that noncalibrated 14C age models may lead to biased conclusions when considering paleoclimatic events. Thus, those records that had the ages out of the MH time interval are, in fact, from more recent periods, and this could only be assured by the calibrated ages. These records are an example of how the age calibration is important, once the the uncertainties from a sample's age are responsible for attributing or not specific characteristic or climate change to a geologic period (Lowe and Walker, 1997).

The compilation by Prado et al. (2013) brought together with the climatic reconstruction of the MH to the east of SA a discussion about the atmospheric dynamics of the region. With the addition of new data and age calibration, Gorenstein et al. could carry out a new, more robust climatic reconstruction for the east of South America. This reconstruction confirmed the scenario of water deficit in the Amazon, a warmer and drier south of South America, as well as the development of saltier conditions along the continental margin of the South America during the Middle Holocene compared to the late Holocene. The border between the Northeast of Brazil and the South of South America and much of the east of the coast of the Northeast of Brazil showed divergences and pointed to local scenarios with humidity conditions higher than the current ones due to the displacements of the Convergence Zone of the South Atlantic and Intertropical and the weakening of the South American monsoon system during HM.

3.3. American Monsoon System variations during the Holocene

The results of this item compose a manuscript from Bianchini et al. that is in preparation. In this artcicle a different dataset from the ones used in the two previous articles was used. During the Holocene period there were several climatic changes on a global scale that had as main drivers the changes in the insolation related to the Earth's orbital variations and solar variability (Mayewski et al., 2004). During this period, the opposite hemispheric trends of solar insolation during the corresponding summer, with the decrease of the insolation in the NH and the increasing insolation in the SH, promoted a redistribution of energy (Wanner et al., 2011). As the distribution of energy in the atmosphere occurs mainly through the transport of water vapor (Mayewski et al., 2004), the redistribution of this energy promoted several global climatic changes during the Holocene, such as the displacement of the Intertropical Convergence Zone (ITCZ) to the south, and the weakening of the summer monsoon systems in the Northern Hemisphere (Braconnot et al., 2007). Therefore, based on the prominent occurrence of abrupt climatic events noticed globally, the Holocene period was recently divided into three distinct stages Greenlandic Stage (11.5-8.2 ka), Northgrippian Stage (8.2-4.2 ka) and Meghalayan Stage (4.2 ka to DC 1950) (Walker et al., 2019).

Climatic variations in AMS during the Holocene have been the focus of several studies (e.g., Aguiar et al., 2020; Cassino et al., 2020). The study of these monsoon system includes the NAMS and SAMS that have been interpreted as two axes of the same cycle that composes the AMS (Vera et al., 2006), since the climatic variability of the NAM can be influenced by that of the SAM, or vice versa, in addition to the variability of the regional land surface and the adjacent oceanic climatic conditions (Fu et al., 2016). During the Holocene period, there is evidence of the classic AMS insolation forcing associated with ITCZ migration, since there is a well-established relationship between the global energy balance and the location of ITCZ cells (Schneider et al., 2014). However, throughout this period there was a decrease in the insolation in the NH and an increase in the insolation in the SH (e.g. Prado et al., 2013). As a result, NAMS weakened over this period, generating drier climatic conditions (Metcalfe et al., 2015; Jiménez-Moreno et al., 2019), and SAMS strengthening, generating more humid climatic conditions (Cassino et al., 2020; Maksic et al., 2018).

Today, most AMS paleoclimatic studies are done with a focus on NAMS or SAMS, rarely holistically, considering them as a single system. This paper from Bianchini et al. is in preparation and seeks to investigate the variations of AMS as a whole during the Holocene period (last 12,000 years) through paleoclimatic and paleoenvironmental studies of lake sediments.

3.3.1. Highlights

- Paleoclimate of the AMS during the Holocene period;
- 41 lake records in AMS area of influence;
- Insolation influence in the AMS pattern.

3.3.2. Preliminary Results

In both North America and South America, there is the characterization of a monsoon system by the presence of the low-level high-level / low-heat anticyclone in the summer, which is in spatial quadrature in longitude with rise on the east side and subsidence on the west side (Chen 2003). In monsoon areas, the dominant force in long-term climate change is heat stroke, predominantly driven by precession (Kutzbach, 1981). In addition, some characteristics such as the distribution of continental masses, orography and sea surface temperatures (SSTs) contribute to define the characteristics of monsoon systems, with some difference between NAMS and SAMS, such as the period of the year in which each of these systems is stronger (Mechoso et al., 2004). To understand the behavior of the AMS in the Holocene period at the broadest scale, it is important to consider all these factors, specially the insolation forcing and the migration fo the the Intertropical Convergence Zone (ITCZ) (Metcalfe et al., 2015).

To understand the behavior of AMS in the Holocene period, the current annual AMS performance standard was used as a basis for comparison (Figure 17). This pattern was obtained from monthly precipitation and surface temperature for the four seasons of the year from a combined data set from the Global Precipitation Climatology Project (GPCP) v2.3 (Adler et al., 2018). The result obtained show that the current influence of AMS is marked by the relationship between the North and South American Monsoon Systems, in which the beginning of NAM contributes to the end of SAM or vice versa (e.g. Fu et al., 2016). This relationship could also be observed during the Holocene period once the results show that the SH started this period with predominantly drier tha present phases, shifting to a predominantly more humid than present phase that persists today (e.g., Aguiar et al., 2020; Prado et al., 2013).

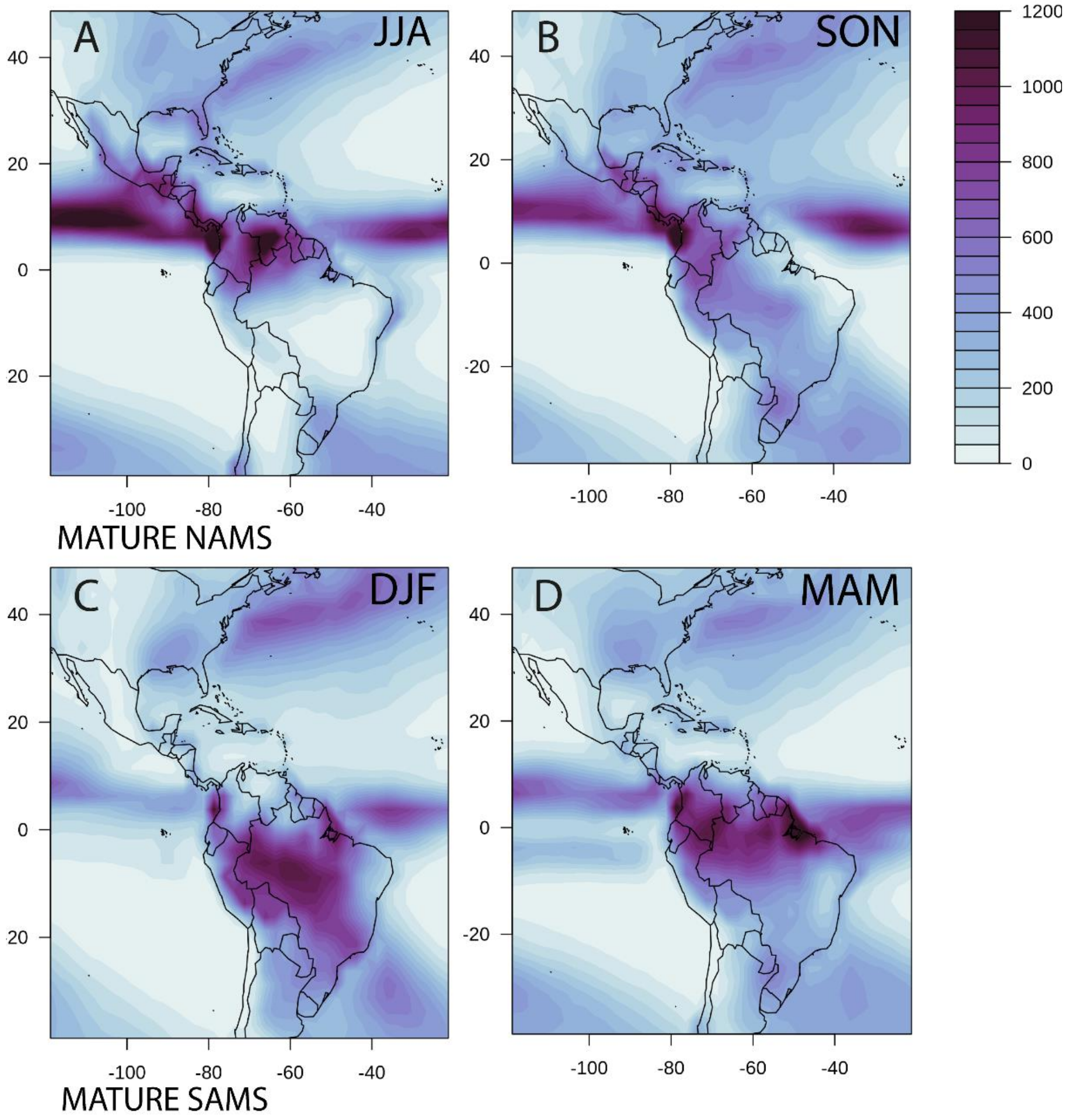

Figure 17. Current American Monsoon System performance standard obtained from accumulated average precipitation (mm / 3 months), calculated from Jan / 1979 to Dec / 2019 for: A) June-August (JJA); B) September-November (SON); C) December-Febreuary (DJF); and D) March-May (MAM).

With a better understanding of the current AMS performance standard, the data from the compilation for this article was used to understand variations in AMS during the Holocene. Of the 115 lakes initially considered, 41 have been chosen for this study for presenting the four main criteria established: being incert in the considered spacial domain (40°N-40°S; 120°W-30°W), being multiproxy studies, having calibrated ages, and being fully insert in the considered temporal domain (12,000-1850 cal years C.E). All lakes and criteria initially considered are displayed in Table 16 (Appendix III). The paleoenvironmental / paleoclimatic reconstructions in these articles contain records that allow analysis of the predominant paleoclimate in the regions of influence of the American Monsoon System (AMS) during the Holocene period, through information of precipitation or moisture. This assessment was made separately for the three periods of the Holocene, as defined by Walker et al. (2019): Early Holocene (EH), Middle Holocene (MH) and Late Holocene (LH), as shown in Table 17 (Appendix III).

Although the climatic signs varied in each of these periods, an average of the description of each period (drier/more humid than present), which is what was considered in this study. The results obtained can be seen in Figure 18.

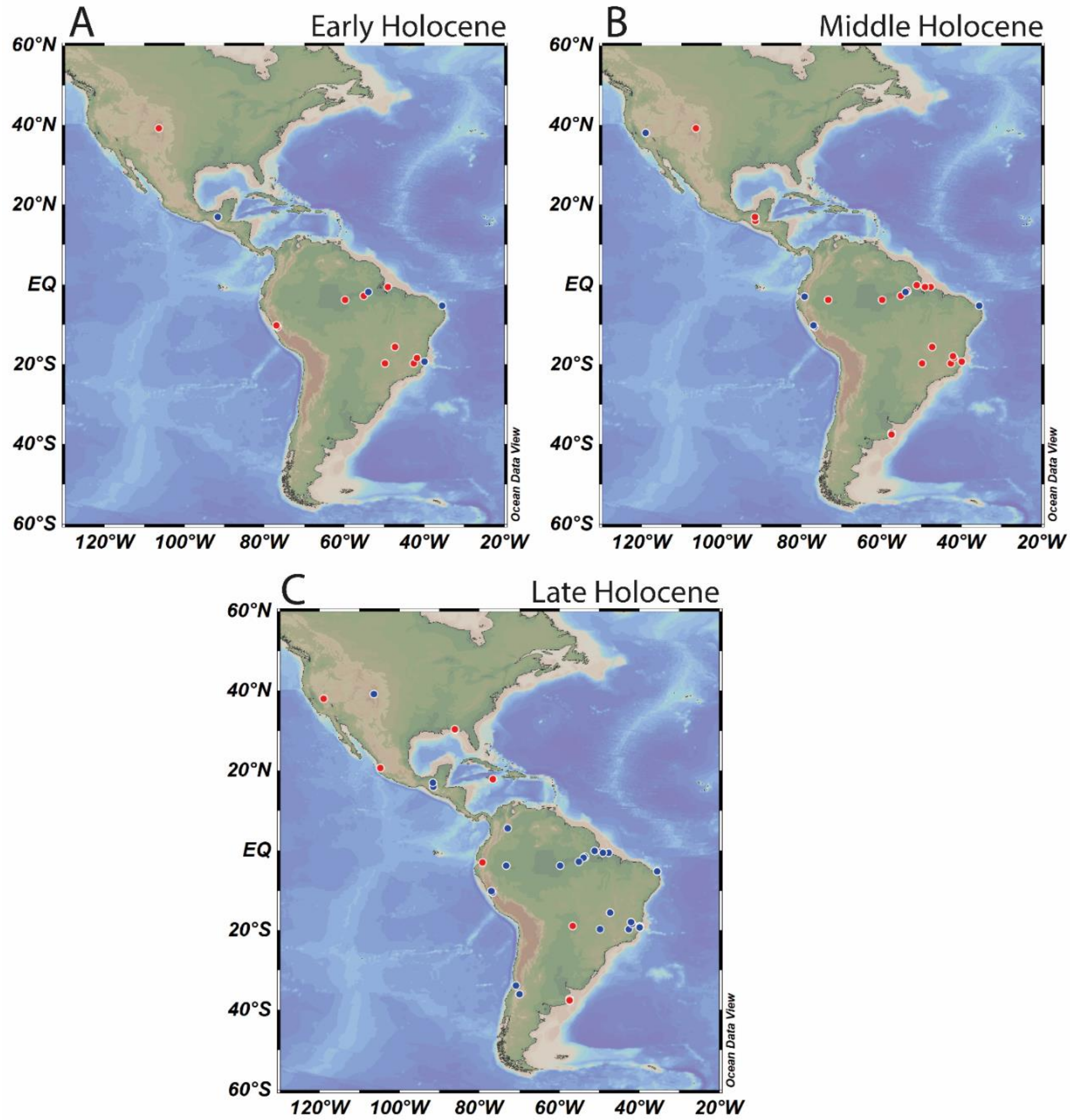

Figure 18. Precipitation/moisture palaeodata in the regions of influence of the American Monsoon System during the: A) EH; B) MH; and C) LH. Symbol colours: blue circles, more humid than present; red circles, drier than present.

The results presented in Figure 18 show that the EH period had only 15 records in the considered studies, having been a predominantly drier than present period in North and South America, and more humid than present in Central America. The MH period had 30 records in the studies considered, having been a predominantly drier than present period across the American continent. The LH period was recorded in all 41 studies considered, having been a predominantly wet than present period throughout the American continent.

In the region where NAMS is predominant the results show differences between the southern and northern regions during the Holocene period. In the northern regions the results show the predominant record of drier than present phases during the whole Holocene period. In the suthern regions the results show the predominant record of more humid than present phases during the EH and LH periods, and of a drier than present period phase during the MH. These results are consistent with those obtained in other studies as Metcalfe et al. (2015) and Jiménez-Moreno et al. (2019) that recorded a predominance of a drier than present pattern that persisted throughout the Holocene period in the northern regions and the beginning of a more humid than present phase in MH and that predominates in LH in the southern regions. This can be explained because with the decrease of the insolation in the NH and the consequent weakening of the NAMS, other forces became more important, such as the location of the ITCZ cells (Faurschou Knudsen et al., 2011). Therefore, as the NH summer and autumn heat stroke declined and the ITCZ went south, the antiphasic pattern that was observed between north and south appeared (Metcalfe et al., 2015).

In the region where SAMS is predominant the results show the predominant record of drier than present phases during the periods of EH and MH, and of a more humid than present phase during the period of LH. These results are consistent with those obtained in other studies as Novello et al. (2017) that recorded a drier than present phase during the EH period, Prado et al. (2013) that recorded a general drier than present phase during the MH period and Utida et al. (2019) that recorded a more humid than present phase during the period of LH. This can be explained because with the increase of the insolation in the SH and with the displacement of the ITCZ towards the south during the Holocene period, there was an increase in the formation of clouds, increasing the amount of precipitation and characterizing a period of more humid climate (e.g., Cassino et al., 2020; Utida et al., 2019).

Changes in insolation patterns since the Holocene period can be pointed out as the main factor to cause the changes observed in the AMS (Cruz et al., 2009). Insolation influences the effectiveness of the land-sea contrast, the amount of energy available for cloud formation and, consequently, the climate (Prado et al., 2013). Data from the summer insolation in Northern and Southern Hemispheres of the last 12000 years were obtained from Berger and Loutre (1991) and are show in Table 18 (Appendix III). These data allowed the calculation of these insolation curves presented

Figure 19. These curves show a declining of the insolation in the NH from the Holocene period with a beginning of insolation growth in the Souther Hemisphere (SH) from that same period, what was also observerd in other studies (e.g. Faurschou Knudsen et al., 2011). This insolation increases in the SH had its peak from the LH period, which corresponds to what was proposed by Cruz et al. (2009). According to them, the changes in the precipitation regime in SA during the Holocene occurred due to changes in the circulation of monsoons, whose main forcing was the changes in the insolation. As the land-sea thermal contrast is the main factor that affects the circulation of monsoon systems (e.g., Vera et al., 2006; da Silva and de Carvalho, 2007) the hemisphere that receives the most sunlight tends to be warmer, promoting more evaporation, greater cloud formation and more precipitation (Prado et al., 2013). Thus, this increase in heat stroke in the SH from the Holocene promoted the formation of clouds, characterizing a period of humid climate that persists today.

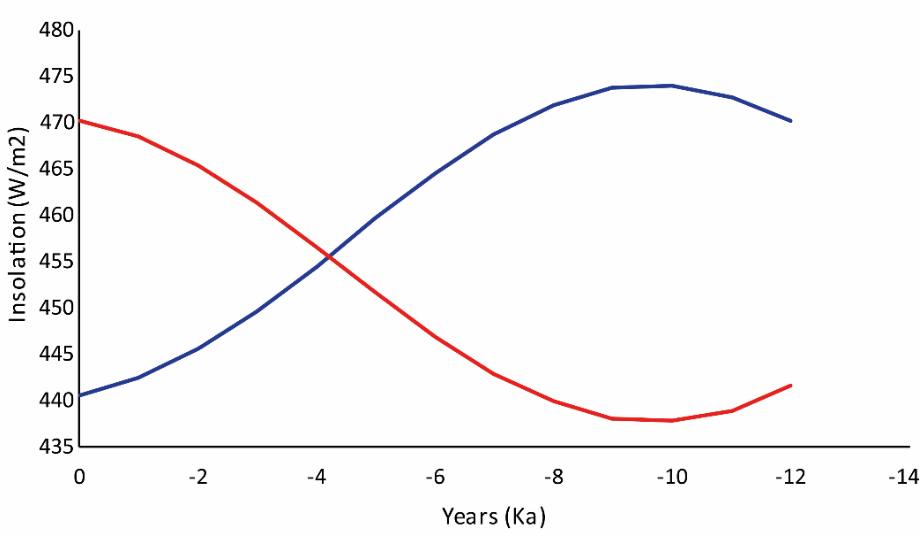

Figure 19. Summer insolation in the Northern (blue line) (15°N) and Southern (red line) (15°S) Hemispheres of the last 12000 years. Data from Berger e Loutre (1991) and available at https://www.ncdc.noaa.gov/paleo-search/study/577.

3.4. Case Study: Lagoa Feia

The results of this item compose a manuscript from Yokoyama et al. that is in preparation. The Lagoa Feia record provides unprecedented insight into landscape and rainfall variability in central Brazil (Cassino et al., 2020). Thus, this study was done to try to understand how the South American Monsoon System influenced the climate of Central Brazil, and what events the Lagoa Feia sediments recorded.

3.4.1. Highlights

- Paleoclimate in central Brazil;
- A new age model for Lagoa Feia;
- Well-defined relationship between elemental ratios and magnetic properties;
- Mid-Holocene climate variability is observed in LBF1 record;
- Precipitation events are represented by variations in elemental and magnetic properties.

3.4.2. Preliminary Results

Lagoa Feia is located near the city of Formosa, State of Goiás, in Central Brazil, as shown in the Figure 20. A.

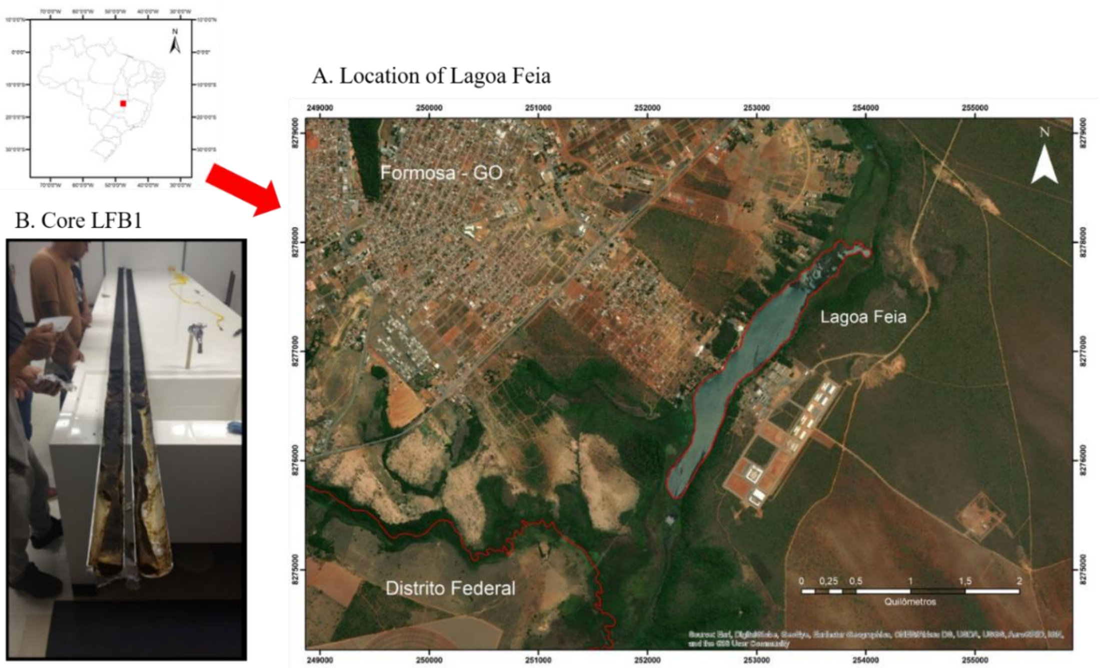

Figure 20. A. Map with the location of Lagoa Feia. B. Opened core LFB1 showing the top with alterations.

In the late 1990's, Turcq and collaborators collected two cores in the Lagoa Feia. One core (LFB2) was analyzed by Turcq et al. (2002) and the twin core (LFB1) is analyzed in the present study. It was observed that the top of the LFB1 core was significantly modified and altered due to the decomposition of organic matter during the period in which the core was stored (Figure 20.B).

3.4.2.1. Age Model

Turcq et al. (2002) calculated an age model for the core LFB2 using twelve ages (Figure 21.A) and found low sedimentation rates with exceptional increases in sedimentation rates observed on the top and at the base of the core. A new age model was calculated using the BACON software (Figure 21. B), and combining ages from Turcq et al. (2002) and five AMS 14C new ages (Table S3). The new age model is more robust than the previous one and has a symmetrical prior accumulation rate and high memory, which indicates that the rate of accumulation has been constant along time (Blaauw and Christen, 2013).

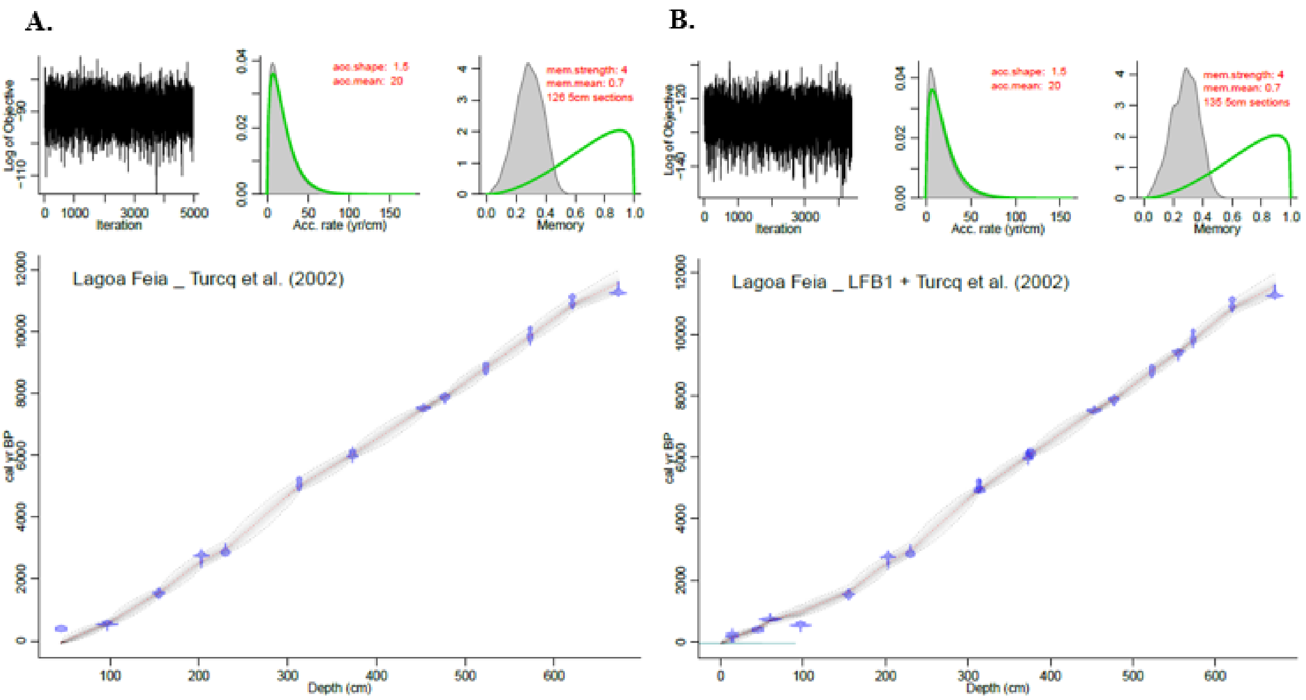

Figure 21. A) Age model obtained with Turcq et al. (2002) data; B) New age model that combines the radiocarbon ages obtained by Turcq et al. (2002) in LBF2 core and five AMS ^{14}C ages obtained from in LBF1 twin core.

3.4.2.2. Principal Component Analysis

All the results of the analysis of the major elements, elements rates and magnetic susceptibilities are presented in Table S3. PCA was computed using the ratios: Ca/(Al+Fe+Ti), Ca/Fe, Fe/Ti, Si/Ti, Ti/Ca and Ti/K, and the parameters χARM, χfd and χARM/χfd magnetic susceptibilities (Figure 22).

PCA shows two main associations: one between calcium ratios (Ca / Fe and CA / Si) and χARM, and another between titanium ratios (Ti / Ca and Ti / K) and χARM / χfd (Figure 22). These results indicate that there is a well-defined covariation relationship between elementary ratios and magnetic properties.

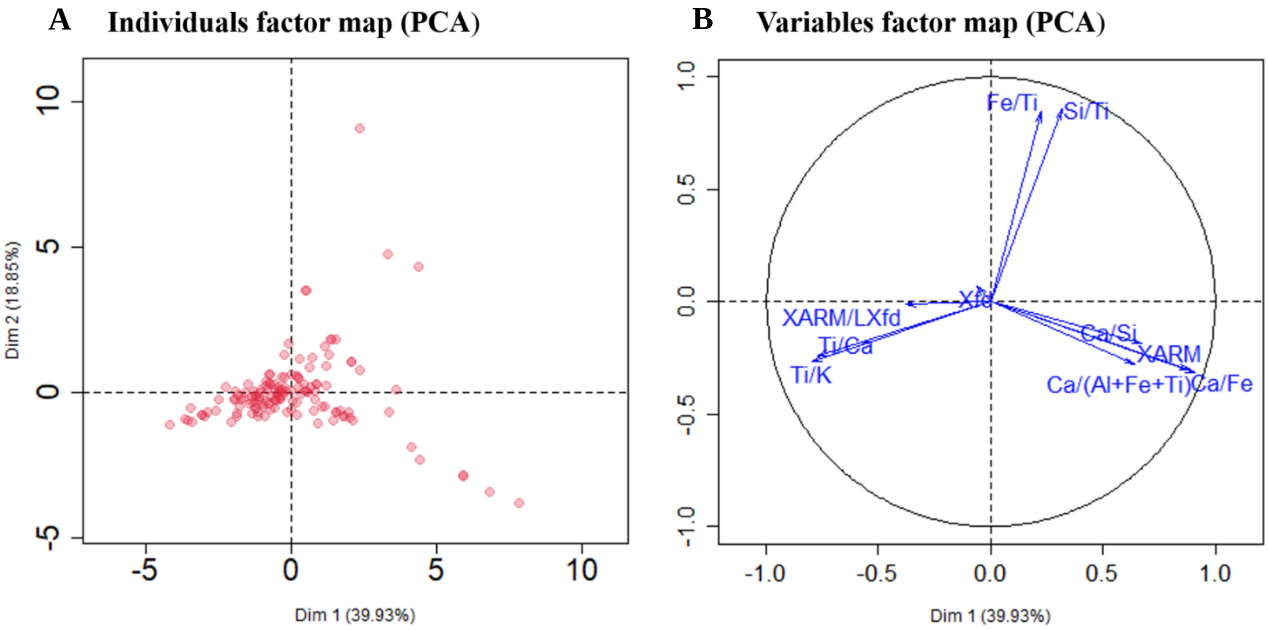

Figure 22. Principal Component Analysis from LFB1 elements and magnetic properties.

3.4.2.3. Multiproxy Analysis

It was made a joint analysis of the new age model, of the magnetic susceptibilities and of the elementar raios of and Ca/(Al+Fe+Ti) and Ca/Si since the PCA showed that these elementary ratios and magnetic properties are covariant and varied together over time (Figure 23). The results presented in Figure 23 allow the identification of precipitation events, represented by variations in magnetic properties and in elemental ratios. The LFB1 core recorded the period that covers the last 8,000 years. It was possible to notice that during this period there was an alternation between drier and wetter periods in the region of Lagoa Feia. In addition, it is possible to observe some most marked periods.

One of these periods occurred around 5000 years ago, with an increase in magnetic susceptibility and a decrease in elementary ratios. The increase in χARM indicates great influx of pedogenic magnetite by sediment uptake, which may indicate wet periods (Mahe, 1988; Wei et al., 2018). The decrease in the Ca/(Al+Fe+Ti) and Ca/Si ratios indicates a decreased authigenic carbonate precipitation, which may indicate wet periods (Jouve et al., 2013; Mueller et al., 2009; Wünnemann et al., 2010). Thus, all the observed parameters show the occurrence of a wetter period around 5000 years. This period seems to have been followed by a drier one, evidenced by the increase in the Ca/(Al+Fe+Ti) and Ca/Si ratios, which indicate an increased authigenic carbonate precipitation, which may indicate a drier period (Jouve et al., 2013; Mueller et al., 2009; Wünnemann et al., 2010).

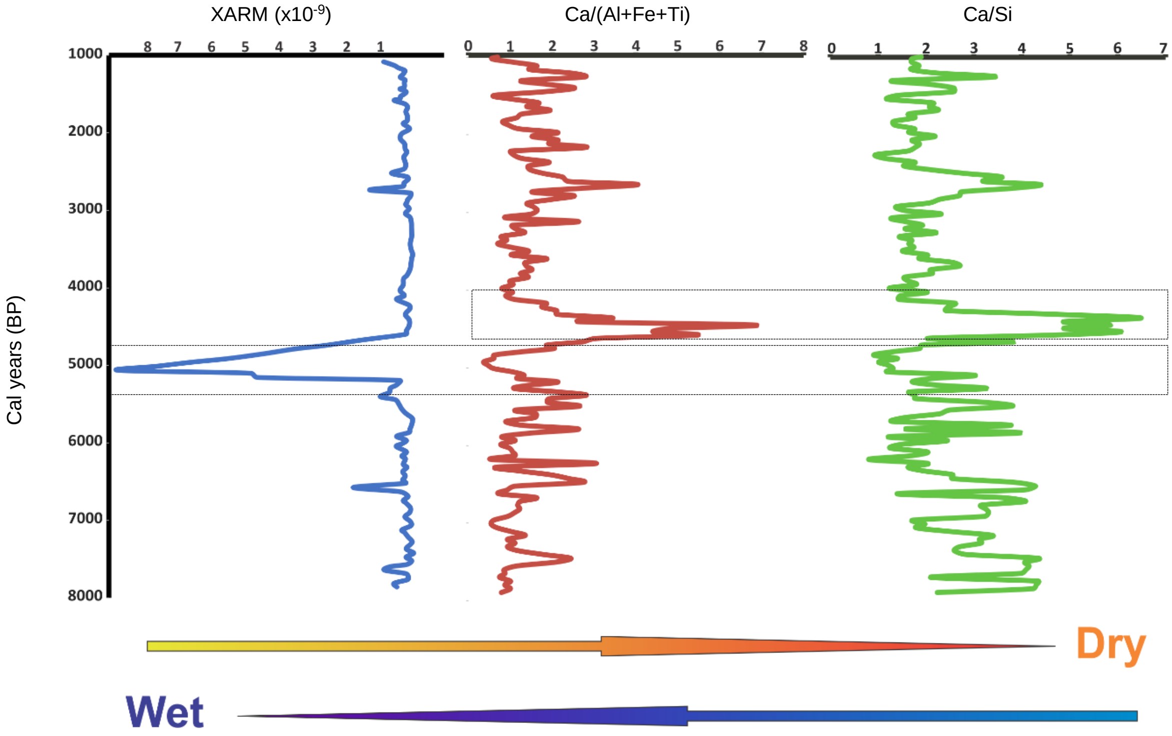

Figure 23. Environmental response to Mid-Holocene climate variability in LFB1 elemental and magnetic properties.

The alternation between the drier and wetter periods observed in the core may be related to the several significant changes in the South American Summer Monsoon (SASM) belt that have occurred in central Brazil in the last 11200 years (Cassino et al., 2020). The Middle Holocene was registered as a predominantly drier than present period, which was confirmed in other works (e.g. Cassino et al., 2018). However, there is a record of a rainier event around the 5000 years, featuring a wetter than present period that seems to coincide with the trends described by Cassino et al. (2020) between ~6500 and 5000 cal yr BP. According to them, the climate conditions in the central Cerrado in this period were relatively wetter, what was also observed in the LFB1 core. The drier period registered aroud 4500 years, on the other hand, may have been the record of a regional event. These results show that Mid-Holocene climate variability is observed in LBF1 record, in addition to possible regional climate change records.

Chapter 4

Final remarks and considerations

This study focoused on how the lake sediments can be used in paleohidroclimate studies in different sacales. For that, paleoclimatic and paleoenvironmental reconstructions made in lake sediments were considered. Initially, a compilation of paleoclimatic studies based on lake sediments was performed, associated with an ^{14}C age model's calibration work. After the understanding of how lakes sediments record climate and environmental changes, a compilation of paleoclimatic and paleoenvironmental studies based on lake sediments in the region of influence oh the AMS was performed, in association with a reanalysis of the sediments of the Lagoa Feia.

This compilation show that lakes' ecosystems are formed by a complex network of biochemical interactions, making it interesting to study the largest number of possible proxies (multiproxy approach) for a broader view of their context than could be acquired from a single proxy (Smol, 2002; NRC, 2005). The multiproxy approach has recently become a common approach in paleolimnological, paleoecological, and sedimentological research to reconstruct the paleoenvironment (Nowacki et al., 2019). No single proxy is adequate to reconstruct large-scale patterns from the past climate (Mann, 2002). By contrast, a multiproxy approach can provide more information about the climate system than the sum of the individual proxies. This occurs because the interpretation based only one parameter or proxy can be misleading and may not address all the complexity of the system (Nowacki et al., 2019). Besides that, well-designed multiproxy studies can provide potentially independent evidence that permit assessing competing hypotheses. This can contribute to a better understanding of how lakes and their biota respond to internal and external events in them, and the strengths and weaknesses of each proxy (Birks and Birks, 2006). This type of approach allows both the direct study of lake responses to climate change in the past and the testing of different hypotheses about lake development (Birks et al., 2010).

Beyond the proxies, an accurate dating is essential in paleoclimatic studies, since the degree of success in discerning patterns of climate and environmental change depends on the level of correlation of paleorecords, which is related to the quality of the age model (Zimmerman and Wahl, 2020). Radiocarbon ages require calibration to obtain calendar ages, since this calibration compensates for the error introduced by conventional half-life (Libby ages) and the temporal variability of the atmospheric ^{14}C content (Hajdas, 2008).

Associated with that, ^{14}C age models examined by Prado et al. (2013) were calibrated to enable a climatic reconstruction of the Middle Holocene (MH) to the east of South America. Reliable estimates of the age of past events are fundamental, because without them it is impossible to investigate whether they occurred at the same time, whether certain events led or delayed others, and it is impossible to accurately assess the rate at which they occurred past environmental changes (Bradley, 1999). It this study 5 recors used by Prado et al. (2013) could not be used anymore because after the calibration of their age models, they were out of the time interval initially considered. It shows that the age model’s calibration is important, once the the uncertainties from a sample's age are responsible for attributing or not specific characteristic or climate change to a geologic period (Lowe and Walker, 1997).

After a better understanding of how lake sediments register paleoclimatic and paleoenvironmental changes the compilation of paleoclimatic and paleoenvironmental studies based on lake sediments in the region of influence oh the AMS. This study shows that since the Holocene period the influence of AMS is marked by the relationship between the North and South American Monsoon Systems, in which the beginning of NAM contributes to the end of SAM or vice versa. Moreover, it was possible to observe that the the performance of the NAMS and SAMS has changed since the Holocene period until today and that this change was influenced by changes in insolation patterns in the northern and southern hemispheres.

The Lagoa Feia record provides unprecedented insight into landscape and rainfall variability in Central Brazil (Cassino et al., 2020) and this reanalysis as a multiproxy study with a new and robust age model composes a reliable record to paleocimatic and paleoenvironmental changes in Central Brazil. The resuls show that the sediments from Lagoa Feia registered some main climatic events that occurred during the Holocene period in that region, as an alternation between the dry and humid periods and an anomalous humid period well marked around 5000 years. These events have been seen in anothers regions and are probably related to the several significant changes in the SAMS that have occurred in Central Brazil in the last 12000 years. In addition, other variations were registered, as a drier period registered aroud 4500 years, that may correspond to a regional event.

This study shows that for paleoclimatic and paleoenvironmental studies based on lake sediments a complete view of the context and characteristics of the lake/basin is required, considering all the climatic and environmental context, a robust and reliable age model with calibrated ages, a sense of the limitations of each proxy and an interpretation of the results based on data alone, not on personal judgments and preexisting concepts. Moreover, it shows that the AMS pattern has been influenced by changes in the insolation patterns since the Holocene period and that the sediments from Lagoa Feia registered some events from the Mid-Holocene climate variability and from some regional events. These studies allow the understanding of how the American monsoon has influenced the climate in Brazil for the past 12000 years, mainly in central Brazil. The next steps for this work would be to compare climate models with the signals from the proxies already obtained, allowing for more robust reconstructions.

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Appendices

Appendix I

I.I. Tables of the scientific article "PALEOCLIMATIC AND PALEOENVIRONMENTAL STUDIES IN LAKE SEDIMENTS: APPLICATIONS, EVOLUTION AND PROXIES"

Table 1. Compiled lakes used in this study.

Lake Reference Number (LRN)	Lake Name	Continent	Lat (°)	Lon (°)	Altitude (m)	P	References
LRN 1	Abiyata	Africa	7.70	38.60	1578	1	Jolly et al. (1998); Kiage and Liu (2006)
LRN 2	Agorgott	Africa	22.65	-4.00	133	1	Jolly et al. (1998); Kiage and Liu (2006)
LRN 3	Ahakagyezi	Africa	-1.08	29.90	1830	1	Jolly et al. (1998)
LRN 4	Badda	Africa	7.87	39.37	4040	1	Jolly et al. (1998)
LRN 5	Barombi	Africa	4.67	9.40	300	1	Jolly et al. (1998)
LRN 6	Blydefontein	Africa	-31.09	25.04	1700	1	Jolly et al. (1998)
LRN 7	Bogoria	Africa	0.30	36.10	990	1	Jolly et al. (1998); Kiage and Liu (2006)
LRN 8	Bosumtwi Lake	Africa	6.50	-1.42	97	5	Jolly et al. (1998); Shanahan et al. (2006); Talbot and Johannessen (1992)
LRN 9	Cederberg	Africa	-32.64	19.33	2026	1	Jolly et al. (1998)

LRN 10	Chemchane	Africa	20.93	-12.22	252	1	Jolly et al. (1998)
LRN 11	Chew Bahir	Africa	4.83	36.77	502**	4	Foerster et al. (2012)
LRN 12	Diogo	Africa	15.27	-16.80	8	1	Jolly et al. (1998)
LRN 13	El Atrun	Africa	18.17	26.65	510	1	Jolly et al. (1998)
LRN 14	Elim	Africa	-28.49	28.42	1890	1	Jolly et al. (1998)
LRN 15	Enneri	Africa	21.33	17.05	1100	1	Jolly et al. (1998)
LRN 16	Equus Cave	Africa	-27.27	24.37	1250	1	Jolly et al. (1998)
LRN 17	Gatovu	Africa	-2.53	30.05	1350	1	Jolly et al. (1998)
LRN 18	Itasy	Africa	-19.00	46.76	1230	1	Jolly et al. (1998)
LRN 19	Kamiranzovu	Africa	-2.33	29.00	1950	1	Jolly et al. (1998)
LRN 20	Karimu	Africa	0.50	36.68	3040	1	Jolly et al. (1998)
LRN 21	Koitoboss	Africa	1.13	34.57	3940	1	Jolly et al. (1998)
LRN 22	Kuruyange	Africa	-3.58	29.68	2000	1	Jolly et al. (1998)
LRN 23	Lake Albert	Africa	1.75	30.97	619	1	Kiage and Liu (2006)
LRN 24	Lake Kasenda	Africa	0.45	30.28	1260	5	Ryves et al. (2011)
LRN 25	Lake Kivu	Africa	-2.10	29.10	1463**	4	Votava et al. (2017)

LRN 26	Lake Malawi	Africa	-12.00	34.50	532**	4	Scholz et al. (2007)
LRN 27	Lake Masoko	Africa	-9.33	33.75	861	1	Kiage and Liu (2006)
LRN 28	Lake Natron/Magadi	Africa	-2.42	36.00	538	2	Horton et al. (2016)
LRN 29	Lake Ngami	Africa	-20.46	22.75	925	4	Cordova et al. (2017)
LRN 30	Lake Rukwa	Africa	-8.09	32.22	793	1	Kiage and Liu (2006)
LRN 31	Lake Simbi	Africa	-0.36	34.62	1145	1	Kiage and Liu (2006)
LRN 32	Lake Solai	Africa	0.06	36.14	1500	1	Goman et al. (2017)
LRN 33	Lake Tana	Africa	12.00	37.25	1830	5	Marshall et al. (2011)
LRN 34	Lake Turkana	Africa	3.63	35.98	361	1	Kiage and Liu (2006)
LRN 35	Lake Wandakara	Africa	0.42	30.23	1170	5	Ryves et al. (2011)
LRN 36	Lompoul	Africa	15.42	-16.72	3	1	Jolly et al. (1998)
LRN 37	Mahoma	Africa	0.34	29.97	2960	1	Jolly et al. (1998)
LRN 38	Moreletta	Africa	-25.44	28.18	1310	1	Jolly et al. (1998)
LRN 39	Mount Kenya	Africa	-0.15	37.30	4473	1	Kiage and Liu (2006)
LRN 40	Mount Kilimanjaro	Africa	-3.07	37.35	5775	1	Kiage and Liu (2006)
LRN 41	Mouskorbe	Africa	22.37	18.53	2600	1	Jolly et al. (1998)

LRN 42	Muchoya	Africa	-1.28	29.80	2260	1	Jolly et al. (1998)
LRN 43	Mukibongo	Africa	-3.15	30.58	1540	1	Jolly et al. (1998)
LRN 44	Naivasha	Africa	-0.75	36.33	1890	1	Jolly et al. (1998)
LRN 45	Ndurumu	Africa	-2.72	29.93	1363	1	Jolly et al. (1998)
LRN 46	Ngamakala	Africa	-4.07	15.38	400	1	Jolly et al. (1998)
LRN 47	Nyamuswaga	Africa	-2.90	29.98	1546	1	Jolly et al. (1998)
LRN 48	Oyo	Africa	19.27	26.18	510	1	Jolly et al. (1998)
LRN 49	Pakhuis	Africa	-32.06	19.04	600	1	Jolly et al. (1998)
LRN 50	Potou	Africa	15.75	-16.50	12	1	Jolly et al. (1998)
LRN 51	Rutundu	Africa	-0.17	37.32	3140	1	Ficken et al. (2002); Jolly et al. (1998)
LRN 52	Sacred	Africa	0.05	37.52	2400	1	Jolly et al. (1998)
LRN 53	Saltpan	Africa	-25.57	28.08	1100	1	Jolly et al. (1998)
LRN 54	Selima	Africa	21.37	29.32	200	1	Jolly et al. (1998)
LRN 55	Sidi Bou Rhaba	Africa	34.25	-6.67	0	1	Jolly et al. (1998)
LRN 56	Tanganyika	Africa	-4.50	29.33	773	1	Alin and Cohen (2003); Burnett et al. (2011); Jolly et al. (1998)

LRN 57	Taoudenni	Africa	22.67	-3.97	120	1	Jolly et al. (1998)
LRN 58	Tate Vondo	Africa	-22.88	30.33	1100	1	Jolly et al. (1998)
LRN 59	Tigalmamine	Africa	32.91	-5.34	1626	1	Jolly et al. (1998)
LRN 60	Tjeri	Africa	13.73	16.50	300	1	Jolly et al. (1998)
LRN 61	Touba N'Diaye	Africa	15.17	-16.87	6	1	Jolly et al. (1998)
LRN 62	Tritrivakely	Africa	-19.78	46.92	1800	1	Jolly et al. (1998)
LRN 63	Victoria	Africa	0.30	33.33	1134	1	Jolly et al. (1998)
LRN 64	Vinaninony	Africa	-19.83	47.33	1875	1	Jolly et al. (1998)
LRN 65	Windhoek	Africa	-22.38	17.50	1700	1	Jolly et al. (1998)
LRN 66	Wondercrater	Africa	-24.43	28.75	1100	1	Jolly et al. (1998)
LRN 67	Wonderwerk	Africa	-27.85	23.55	1665	1	Jolly et al. (1998)
LRN 68	Chandra Lake	Asia	32.48	77.62	4281	4	Rawat et al. (2015)
LRN 69	Cuoe Lake	Asia	31.47	91.50	4532	5	Yanhong et al. (2006)
LRN 70	Dahu Swamp	Asia	24.45	115.02	246	3	Wei et al. (2018)
LRN 71	Daihai Lake	Asia	40.56	112.68	1225	1	Xu et al. (2010)
LRN 72	Dali Lake	Asia	43.33	116.50	1230	3	Liu et al. (2016)

LRN 73	Ennamangalam Lake	Asia	11.65	77.59	265	3	Mishra et al. (2019)
LRN 74	Gahai Lake	Asia	34.25	102.33	3482**	1	Duan et al. (2016)
LRN 75	Hulun Lake	Asia	49.20	117.50	545	4	Xiao et al. (2018)
LRN 76	Jalesar Lake	Asia	26.61	80.37	137**	4	Trivedi et al. (2013)
LRN 77	Kanas Lake	Asia	48.83	86.98	1362	3	Zhou et al. (2018)
LRN 78	Kolleru Lake	Asia	16.63	81.25	3	3	Basavaiah et al. (2015)
LRN 79	Lake Acigol	Asia	37.71	33.67	987**	4	Demory et al. (2020)
LRN 80	Lake Ahung	Asia	31.62	92.06	4575	2	Horton et al. (2016)
LRN 81	Lake Aktas	Asia	41.20	43.20	-1798	5	Kılıç et al. (2018)
LRN 82	Lake Bangong	Asia	33.70	79.00	4241	2	Horton et al. (2016)
LRN 83	Lake Bolgoda	Asia	6.75	79.92	12**	5	Gayantha et al. (2017)
LRN 84	Lake Chenghai	Asia	26.50	100.67	1503	4	Sun et al. (2019)
LRN 85	Lake Donggi Cona	Asia	35.32	98.53	4090	2	Saini et al. (2017)
LRN 86	Lake Erhel	Asia	49.93	99.92	1544**	4	Katsuta et al. (2017)
LRN 87	Lake Hazar	Asia	38.48	39.40	1255	4	Eris et al. (2018)
LRN 88	Lake Hovsgol	Asia	50.88	100.36	2311**	4	Katsuta et al. (2017)

LRN 89	Lake Huguang Maar	Asia	21.90	110.17	MI	4	Yancheva et al. (2007)
LRN 90	Lake Iznik	Asia	40.43	29.51	88	1	Miebach et al. (2016)
LRN 91	Lake Kinneret	Asia	32.80	35.59	-210	4	Vossel et al. (2018)
LRN 92	Lake Kumphawapi	Asia	17.11	103.02	170	5	Chawchai et al. (2013)
LRN 93	Lake Lisan	Asia	31.50	35.00	-200	2	Horton et al. (2016)
LRN 94	Lake Lop Nur	Asia	40.44	90.68	780	5	Chao et al. (2009)
LRN 95	Lake Pa Kho	Asia	17.10	102.93	175	5	Chawchai et al. (2015)
LRN 96	Lake Qinghai	Asia	37.06	100.30	3192	2	Henderson et al. (2003); Horton et al. (2016); Ji et al. (2005); Lister et al. (1991); Liu et al. (2007, 2009a); Shen et al. (2005); Xu et al. (2006)
LRN 97	Lake Siling	Asia	31.75	89.00	4500	2	Horton et al. (2016)
LRN 98	Lake Son Kol	Asia	41.80	75.10	3016	4	Schwarz et al. (2017)
LRN 99	Lake Suigetsu	Asia	35.58	135.38	0	3	Marshall et al. (2012)
LRN 100	Lake Tso Moriri	Asia	32.90	78.32	4527	4	Leipe et al. (2014); Mishra et al. (2014)
LRN 101	Lake Tuosu	Asia	37.13	96.93	2800	2	Li et al. (2016)

LRN 102	Lake Van	Asia	38.63	42.76	1674	5	Baumgarten et al. (2014); Litt et al. (2009); Stockhecke et al. (2014)
LRN 103	Lake Xiangshui	Asia	25.42	107.88	310	2	Horton et al. (2016)
LRN 104	Lake Zabuye	Asia	31.35	84.07	4421	2	Horton et al. (2016)
LRN 105	Lake Zoige	Asia	33.95	102.35	3400	2	Horton et al. (2016)
LRN 106	Longmu Co Lake	Asia	34.60	80.44	5004	3	Liu et al. (2016)
LRN 107	Manasbal Lake	Asia	34.25	74.67	1583	4	Babeesh et al. (2019)
LRN 108	Nal Sarovar Paleolake	Asia	22.80	72.00	6**	4	Prasad et al. (1997)
LRN 109	Nameless Paleolake	Asia	43.87	146.80	MI	1	Nazarova et al. (2017)
LRN 110	Padauna Swamp	Asia	22.41	81.45	517**	4	Chauhan et al. (2013)
LRN 111	Paiku Co Lake	Asia	28.85	85.60	4585	1	Wünnemann et al. (2015)
LRN 112	Pariyaj Lake	Asia	22.54	72.61	15**	4	Raj et al. (2015)
LRN 113	Pookot Lake	Asia	11.54	76.03	770	4	Bhattacharyya et al. (2015); Veena et al. (2014)
LRN 114	PT Tso Lake	Asia	27.76	91.96	3935	4	Mehrotra et al. (2019)
LRN 115	Sangla Valley	Asia	31.20	78.20	-1890**	4	Ranhotra et al. (2018)

LRN 116	Shantisagara Lake	Asia	14.13	75.90	620**	5	Sandeep et al. (2017)
LRN 117	Sihailongwan Maar Lake	Asia	42.28	126.60	797	1	Stebich et al. (2015)
LRN 118	Sumxi Co Lake	Asia	34.60	80.24	5058	3	Liu et al. (2016)
LRN 119	TCQH Lake	Asia	25.13	98.57	1885	1	Tian et al. (2019)
LRN 120	Tian E'Lake	Asia	39.14	97.55	3012	3	Yan et al. (2020)
LRN 121	Triloknath Palaeolake	Asia	32.66	76.71	3500	4	Bali et al. (2017)
LRN 122	Tso Kar Lake	Asia	33.3	78.00	4527	4	Bhattacharyya (1989); Wünnemann et al. (2010)
LRN 123	Ziro Lake	Asia	27.53	93.83	1600	1	Ghosh et al. (2014)
LRN 124	Grape Tree Pond	Central America	17.53	-76.37	MI	4	Burn and Palmer (2014)
LRN 125	Lake Petén Itzá	Central America	17.00	-89.80	110**	4	Grauel et al. (2016)
LRN 126	Lake Wallywash	Central America	17.97	-77.81	7	2	Horton et al. (2016)
LRN 127	Lake Syrytkul	Europe	55.33	60.25	358	4	Maslennikova and Udachin (2017); Maslennikova et al. (2016)
LRN 128	Lake Vankavad	Europe	65.99	59.46	600	4	Sarmaja-Korjonen et al. (2003)
LRN 129	Antu Sinjätrv	Europe	59.06	26.24	94,6	1	Harrison et al. (1993)

LRN 130	Bjäresjö	Europe	55.46	13.75	53	1	Harrison and Digerfeldt (1993)
LRN 131	Bysjön	Europe	55.68	13.55	22	1	Harrison and Digerfeldt (1993)
LRN 132	Chalain	Europe	46.68	5.80	488	1	Harrison et al. (1993)
LRN 133	El Tobar Lake	Europe	40.55	-2.05	1200	4	Barreiro-Lostres et al. (2015)
LRN 134	Gormire Lake	Europe	54.24	-1.22	140	4	Oldfield et al. (2003)
LRN 135	Havnardalsmyren Palaeolake	Europe	62.01	-6.84	157**	3	Kylander et al. (2012)
LRN 136	Hières-sur-Amby	Europe	45.79	5.29	212	1	Harrison et al. (1993)
LRN 137	Issarlès	Europe	44.82	4.07	997	1	Harrison et al. (1993)
LRN 138	Kaali	Europe	58.37	22.67	13,5	1	Harrison et al. (1993)
LRN 139	Kalina	Europe	59.28	27.33	70	1	Harrison et al. (1993)
LRN 140	Kharinei Lake	Europe	67.21	62.45	108	1	Jones et al. (2011)
LRN 141	Kirikumäe	Europe	57.68	27.25	183	1	Harrison et al. (1993)
LRN 142	Krageholmssjön	Europe	55.50	13.74	43	1	Harrison and Digerfeldt (1993)
LRN 143	Kyrtyma Lake	Europe	56.99	65.83	54**	4	Ryabogina et al. (2019)
LRN 144	Lac de Saint-Ldger	Europe	44.47	6.28	1308	1	Digerfeldt et al. (1997)

LRN 145	Lago Enol	Europe	43.27	-4.99	1070	4	Morellón et al. (2018); Moreno et al. (2011)
LRN 146	Lago Maggiore	Europe	45.95	8.63	194	3	Kämpf et al. (2012)
LRN 147	Lagoa Comprida	Europe	40.36	-7.64	1600	1	Harrison and Digerfeldt (1993)
LRN 148	Laguna de las Madres	Europe	37.16	-6.85	20	1	Harrison and Digerfeldt (1993)
LRN 149	Laguna de las Sanguijuelas	Europe	42.11	-6.71	1050	1	Harrison and Digerfeldt (1993)
LRN 150	Laguna de Medina	Europe	36.62	-6.05	30	1	Reed et al. (2001)
LRN 151	Laguna Grande	Europe	42.03	-3.02	1500	5	Morellón et al. (2018)
LRN 152	Laguna Salada	Europe	37.04	-4.84	452	4	Schröder et al. (2018)
LRN 153	Lake Albano	Europe	41.74	12.66	293	4	Ariztegui et al. (2001)
LRN 154	Lake Ammersee	Europe	48.01	11.11	533	3	Czymzik et al. (2013)
LRN 155	Lake Arakhlei	Europe	52.20	112.90	961**	4	Ptitsyn et al. (2014)
LRN 156	Lake Baikal	Europe	53.00	107.00	-1165**	4	Karabanov et al. (2000); Phedorin et al. (1998)
LRN 157	Lake Banyoles	Europe	42.12	2.75	173	5	Morellón et al. (2018)
LRN 158	Lake Beloye	Europe	55.49	82.83	107	5	Krivonogov et al. (2012)

LRN 159	Lake Bistensee	Europe	54.39	9.68	12**	4	Hübener et al. (2009)
LRN 160	Lake Blanc	Europe	45.58	6.53	2352	3	Wilhelm et al. (2013)
LRN 161	Lake Bled	Europe	46.36	14.09	475	4	Andrič et al. (2009)
LRN 162	Lake Bourget	Europe	45.78	5.83	232**	3	Arnaud et al. (2012)
LRN 163	Lake Bramant	Europe	45.20	6.17	2500	4	Guyard et al. (2007)
LRN 164	Lake Butrint	Europe	39.78	20.02	0**	4	Morellón et al. (2016)
LRN 165	Lake Dojran	Europe	41.20	22.73	144	1	Masi et al. (2018)
LRN 166	Lake El’gygytgyn	Europe	67.50	172.00	497**	4	Melles et al. (2012); Zhao et al. (2015)
LRN 167	Lake Estanya	Europe	42.03	0.53	670	5	Morellón et al. (2018)
LRN 168	Lake Fuentillejo	Europe	38.93	-4.05	640	5	Morellón et al. (2018)
LRN 169	Lake Galgan	Europe	71.91	82.69	17**	4	Fedotov et al. (2012)
LRN 170	Lake Gorgana	Europe	44.07	26.16	29**	5	Nowacki et al. (2019)
LRN 171	Lake Gudower See	Europe	53.54	10.76	25**	4	Hübener et al. (2009)
LRN 172	Lake Hakluytvatnet	Europe	79.77	10.73	12	4	Gjerde et al. (2018)
LRN 173	Lake Ioannina	Europe	39.67	20.88	469	1	Harrison and Digerfeldt (1993)
LRN 174	Lake Jues	Europe	51.64	10.51	1142	1	Voigt et al. (2008)

LRN 175	Lake Kastoria	Europe	40.55	21.32	650	1	Harrison and Digerfeldt (1993)
LRN 176	Lake Kellersee	Europe	54.17	10.59	25**	4	Hübener et al. (2009)
LRN 177	Lake Khimaditis	Europe	40.60	21.57	560	1	Harrison and Digerfeldt (1993)
LRN 178	Lake Kleiner Ploner See	Europe	54.15	10.39	21**	4	Hübener et al. (2009)
LRN 179	Lake Kråkenes	Europe	62.03	5.00	40**	3	Bakke et al. (2009)
LRN 180	Lake Lautrey	Europe	46.59	5.86	788	5	Magny et al. (2006)
LRN 181	Lake Loitsana	Europe	67.80	29.28	214	4	Shala et al. (2014)
LRN 182	Lake Lucenza	Europe	42.58	-7.10	1375	5	Morellón et al. (2018)
LRN 183	Lake Makarov	Europe	71.94	82.67	31**	4	Fedotov et al. (2012)
LRN 184	Lake Meerfelder Maar	Europe	50.10	6.75	336	4	Martin-Puertas et al. (2012); Poth and Negendank (1993)
LRN 185	Lake Mondsee	Europe	47.80	13.40	481	4	Lauterbach et al. (2011)
LRN 186	Lake Montcortès	Europe	42.33	0.99	1027	3	Corella et al. (2012)
LRN 187	Lake Narlay	Europe	46.64	5.91	749**	4	Belle et al. (2016)
LRN 188	Lake Ohau	Europe	-44.23	169.85	520	3	Roop et al. (2016)

LRN 189	Lake Ohrid	Europe	41.01	20.73	693	4	Kousis et al. (2018); Panagiotopoulos et al. (2020); Sadori et al. (2016); Vogel et al. (2010)
LRN 190	Lake Pavin	Europe	45.49	2.89	1197	4	Chassiot et al. (2018)
LRN 191	Lake Prespa	Europe	40.87	21.00	849	4	Aufgebauer et al. (2012); Damaschke et al. (2013)
LRN 192	Lake Ruidera/Alcaraz	Europe	38.93	-2.90	950	2	Horton et al. (2016)
LRN 193	Lake Salines	Europe	38.5	-0.88	475	5	Morellón et al. (2018)
LRN 194	Lake Sanabria	Europe	42.12	-6.72	1000	5	Morellón et al. (2018)
LRN 195	Lake Słone	Europe	51.18	23.21	185	1	Kulesza et al. (2012)
LRN 196	Lake Steisslingen	Europe	47.80	8.92	446	2	Horton et al. (2016)
LRN 197	Lake Stolper See	Europe	54.12	10.23	28**	4	Hübener et al. (2009)
LRN 198	Lake Taravilla	Europe	40.65	-1.97	1100	5	Horton et al. (2016); Moreno et al. (2008)
LRN 199	Lake Tresdorfer See	Europe	54.23	10.46	25**	4	Hübener et al. (2009)
LRN 200	Lake Uddelermeer	Europe	52.25	5.76	26	1	Engels et al. (2016)
LRN 201	Lake Ufimskoe	Europe	1.53	60.11	472	4	Maslennikova and Udachin (2017)

LRN 202	Lake Vegoritis	Europe	40.75	21.76	570	1	Harrison and Digerfeldt (1993)
LRN 203	Lake Villarquemado	Europe	40.50	-1.30	987	5	Morellón et al. (2018)
LRN 204	Lake Vuoksjávrátje	Europe	66.23	15.72	850	4	Berntsson et al. (2014)
LRN 205	Lake Xinias	Europe	39.07	22.26	500	1	Harrison and Digerfeldt (1993)
LRN 206	Landos	Europe	44.84	3.82	1000	1	Harrison et al. (1993)
LRN 207	Le Grand Lemps	Europe	45.46	5.41	456	1	Harrison et al. (1993)
LRN 208	Le Locle	Europe	47.05	6.72	915	1	Magny et al. (2001)
LRN 209	Les Echets	Europe	45.80	4.95	267	4	Kylander et al. (2011)
LRN 210	Loudias Lake	Europe	40.58	22.67	3**	4	Styllas and Ghilardi (2017)
LRN 211	Lyngsjö	Europe	55.93	14.07	63	1	Harrison and Digerfeldt (1993)
LRN 212	Malo Jezero	Europe	42.78	17.35	0	1	Harrison and Digerfeldt (1993)
LRN 213	Padul	Europe	37.02	-3.60	785	1	Harrison and Digerfeldt (1993)
LRN 214	Päidre	Europe	58.27	25.77	50,6	1	Harrison et al. (1993)
LRN 215	Paladru	Europe	45.44	5.52	492	1	Harrison et al. (1993)
LRN 216	Palu	Europe	45.03	13.70	0	1	Harrison and Digerfeldt (1993)
LRN 217	Pellèautier	Europe	44.52	6.01	975	1	Harrison et al. (1993)

LRN 218	Punso	Europe	57.68	27.26	183,2	1	Harrison et al. (1993)
LRN 219	Raigastvere	Europe	58.60	26.64	51,8	1	Harrison et al. (1993)
LRN 220	Saint-Julien-de-Ratz	Europe	45.35	5.65	650	1	Harrison et al. (1993)
LRN 221	Sandsjön	Europe	56.77	13.39	158	1	Harrison et al. (1993)
LRN 222	Solniki Palaeolake	Europe	52.98	23.29	143	4	Mirosław-Grabowska et al. (2015)
LRN 223	Staroje Lake	Europe	52.85	30.97	130	4	Zernitskaya et al. (2015)
LRN 224	Torreberga	Europe	55.63	13.23	8	1	Harrison and Digerfeldt (1993)
LRN 225	Tuuljätrv	Europe	57.70	27.06	257	1	Harrison et al. (1993)
LRN 226	Unterer Landschitzsee	Europe	47.26	13.84	1778	4	Schmidt et al. (2002)
LRN 227	Växjösjön	Europe	56.52	14.48	161	1	Harrison and Digerfeldt (1993)
LRN 228	Vielangen	Europe	56.31	14.41	93	1	Harrison and Digerfeldt (1993)
LRN 229	Windermere	Europe	54.37	-2.94	40**	3	Miller et al. (2014)
LRN 230	Adobe*	North America	37.91	-118.6	1951	MI	Harrison and Metcalfe (1985)
LRN 231	Annie	North America	27.30	-81.40	26	3	Harrison (1989)
LRN 232	Arch*	North America	34.08	-103.08	1174	MI	Harrison and Metcalfe (1985)
LRN 233	Beaver Lake	North America	44.55	-123.18	69	1	Walsh et al. (2010)

LRN 234	Blackwater Draw*	North America	34.25	-103.33	1250	MI	Harrison and Metcalfe (1985)
LRN 235	Bonneville	North America	40.90	-112.40	1280	2	Harrison and Metcalfe (1985); Horton et al. (2016)
LRN 236	Browns Lake	North America	40.68	-82.06	290	3	Harrison (1989)
LRN 237	Cahaba Pound	North America	33.41	-86.76	133	4	Harrison (1989)
LRN 238	Cape Bounty	North America	74.89	-109.59	15**	3	Cuven te al. (2010)
LRN 239	Chewaucan*	North America	42.67	-120.50	1296	MI	Harrison and Metcalfe (1985)
LRN 240	Clark*	North America	33.33	-116.30	169	MI	Harrison and Metcalfe (1985)
LRN 241	Cochise*	North America	32.13	-109.85	1260	MI	Harrison and Metcalfe (1985)
LRN 242	Deep Spring	North America	37.28	-118.03	1499	3	Harrison and Metcalfe (1985)
LRN 243	Dixie*	North America	39.81	-118.00	1027	MI	Harrison and Metcalfe (1985)
LRN 244	Duck Pond	North America	41.93	-70.00	1	4	Harrison (1989)
LRN 245	East Lake	North America	74.53	109.32	5	3	Cuven te al. (2011)
LRN 246	Elegante Crater*	North America	31.8	-113.52	1190	MI	Harrison and Metcalfe (1985)
LRN 247	Estancia*	North America	34.58	-105.6	1842	MI	Harrison and Metcalfe (1985)
LRN 248	Fallen Leaf Lake	North America	38.89	-120.06	166**	5	Noble et al. (2016)

LRN 249	Fiddlers Pond	North America	56.25	-120.74	630	1	Harrison and Metcalfe (1985)
LRN 250	Fort Rock*	North America	43.15	-120.85	1311	MI	Harrison and Metcalfe (1985)
LRN 251	George	North America	43.52	-73.65	96	4	Harrison (1989)
LRN 252	Goshen Springs	North America	31.72	-86.13	105	4	Harrison (1989)
LRN 253	Guthrie	North America	33.09	-101.80	914	1	Harrison and Metcalfe (1985)
LRN 254	Harney*	North America	43.20	-119.10	1246	MI	Harrison and Metcalfe (1985)
LRN 255	Hastings*	North America	53.42	-112.88	739	MI	Harrison and Metcalfe (1985)
LRN 256	Hook Lake Bog	North America	42.95	-89.33	260	4	Harrison (1989)
LRN 257	Isle*	North America	52.62	-114.43	700	MI	Harrison and Metcalfe (1985)
LRN 258	Ketlle Hole Lake	North America	43.00	-95.00	427	4	Harrison (1989)
LRN 259	Kirchner Marsh	North America	44.83	-92.79	275	4	Harrison (1989)
LRN 260	Laguna de Juanacatlán	North America	20.37	-104.44	2000	3	Metcalfe et al. (2010)
LRN 261	Laguna Salada	North America	34.34	-109.71	1920	1	Harrison and Metcalfe (1985)
LRN 262	Lahontan	North America	40.00	-119.50	1054	2	Harrison and Metcalfe (1985); Horton et al. (2016)
LRN 263	Lake Bear	North America	42.00	-111.33	1805	2	Horton et al. (2016)

LRN 264	Lake Big Soda	North America	39.52	-118.88	1216	2	Horton et al. (2016)
LRN 265	Lake Cahuilla	North America	33.40	-116.05	24	2	Horton et al. (2016)
LRN 266	Lake Castor	North America	48.53	-119.55	596	2	Horton et al. (2016)
LRN 267	Lake Chapala	North America	20.10	-103.00	1500	3	Morales et al. (2019)
LRN 268	Lake Chichancanab	North America	20.00	-90.00	38	4	Harrison and Metcalfe (1985); Hodell et al. (2012)
LRN 269	Lake Crawford	North America	43.47	-79.95	150	2	Horton et al. (2016)
LRN 270	Lake Deep	North America	47.68	-95.37	411	2	Horton et al. (2016)
LRN 271	Lake Elk	North America	45.87	-95.80	366	5	Horton et al. (2016); Harrison (1989)
LRN 272	Lake Farewell	North America	62.55	-153.63	320	2	Horton et al. (2016)
LRN 273	Lake Fayetteville Gren	North America	43.03	-75.97	70	2	Horton et al. (2016)
LRN 274	Lake Foy	North America	48.17	-114.36	1004	2	Horton et al. (2016)
LRN 275	Lake Jellybean	North America	60.35	-134.80	730	2	Horton et al. (2016)
LRN 276	Lake Keche	North America	68.02	-146.92	740	2	Horton et al. (2016)
LRN 277	Lake Kepler	North America	61.55	-149.21	26	2	Horton et al. (2016)
LRN 278	Lake Medicine	North America	44.82	-97.35	519	2	Horton et al. (2016)

LRN 279	Lake Mono	North America	38.00	-119.00	1945	2	Hodelka et al. (2020); Horton et al. (2016)
LRN 280	Lake Ocotalito	North America	16.95	-91.60	920	5	Díaz et al. (2017)
LRN 281	Lake Owens	North America	36.43	-117.95	1084	2	Horton et al. (2016)
LRN 282	Lake San Luis	North America	37.68	-105.72	2300	2	Horton et al. (2016)
LRN 283	Lake Seven Mile	North America	62.18	-136.38	520	2	Horton et al. (2016)
LRN 284	Lake SS85	North America	66.97	-51.05	150	5	Olsen et al. (2013)
LRN 285	Lake Twiss	North America	43.45	-79.95	150	2	Horton et al. (2016)
LRN 286	Las Vegas*	North America	36.32	-115.18	697	MI	Harrison and Metcalfe (1985)
LRN 287	Lea County*	North America	33.45	-103.16	1189	MI	Harrison and Metcalfe (1985)
LRN 288	Leconte	North America	33.33	-115.90	-71	3	Harrison and Metcalfe (1985)
LRN 289	Little Salt Spring	North America	27.08	-82.23	5	4	Harrison (1989)
LRN 290	Lubbock*	North America	33.64	-101.89	975	MI	Harrison and Metcalfe (1985)
LRN 291	Manitoba	North America	51.00	-98.80	248	4	Harrison and Metcalfe (1985)
LRN 292	Manix*	North America	35.05	-116.70	130	MI	Harrison and Metcalfe (1985)
LRN 293	Manly	North America	36.18	-116.80	-86	3	Harrison and Metcalfe (1985)
LRN 294	Mendota	North America	43.10	-89.42	257	4	Harrison (1989)

LRN 295	Mexico	North America	19.50	-99.00	2240	1	Harrison and Metcalfe (1985)
LRN 296	Mohave	North America	35.37	-116.13	276	3	Harrison and Metcalfe (1985)
LRN 297	Moon Lake	North America	46.86	-98.16	444	1	Laird et al. (1998)
LRN 298	Mound*	North America	33.09	-102.11	960	MI	Harrison and Metcalfe (1985)
LRN 299	Mud	North America	29.30	-81.87	8	4	Harrison (1989)
LRN 300	Nettilling Lake	North America	65.95	-71.28	56**	4	Chapligin et al. (2016)
LRN 301	Okoboji	North America	43.37	-95.15	423	4	Harrison (1989)
LRN 302	Old Field Swamp	North America	37.12	-89.83	97	1	Harrison (1989)
LRN 303	Orange Lake	North America	29.46	-82.18	18**	1	Brenner et al. (1999)
LRN 304	Panamint*	North America	35.95	-117.23	317	MI	Harrison and Metcalfe (1985)
LRN 305	Pâtzcuaro	North America	19.58	-101.58	2044	1	Harrison and Metcalfe (1985)
LRN 306	Pickerel	North America	45.51	-97.28	564	4	Harrison (1989)
LRN 307	Portales Valley*	North America	34.44	-103.83	1177	MI	Harrison and Metcalfe (1985)
LRN 308	Rich*	North America	33.28	-102.20	1006	MI	Harrison and Metcalfe (1985)
LRN 309	Russell*	North America	38.04	-118.92	1951	MI	Harrison and Metcalfe (1985)
LRN 310	Rutz	North America	44.87	-93.86	314	4	Harrison (1989)

LRN 311	San Agustin*	North America	33.83	-108.17	2065	MI	Harrison and Metcalfe (1985)
LRN 312	San Bartolo Playa*	North America	29.05	-111.95	5	MI	Harrison and Metcalfe (1985)
LRN 313	Searles*	North America	35.70	-117.30	493	MI	Harrison and Metcalfe (1985)
LRN 314	Simpson Lagoon	North America	70.53	-149.62	-1,5**	3	Hanna et al. (2018)
LRN 315	Skinny Lake	North America	57.63	-129.81	910	4	Spooner et al. (2002)
LRN 316	Smallboy	North America	53.58	-114.13	762	1	Harrison and Metcalfe (1985)
LRN 317	Stinky Lake	North America	62.75	-136.63	600	1	Pienitz et al. (2000)
LRN 318	Sunfish	North America	43.47	-80.63	365	4	Harrison (1989)
LRN 319	Szabo Pond	North America	40.39	-74.48	29	4	Harrison (1989)
LRN 320	Taylor Lake	North America	45.22	-62.26	190	4	Spooner et al. (2002)
LRN 321	Teel*	North America	38.21	-118.34	1495	MI	Harrison and Metcalfe (1985)
LRN 322	Titicut Swamp	North America	41.95	-71.03	20	3	Harrison (1989)
LRN 323	Track Lake	North America	66.89	-145.17	145	5	Anderson et al. (2018)
LRN 324	Tulare*	North America	36.00	-119.67	57	MI	Harrison and Metcalfe (1985)
LRN 325	Twelvemile Lake	North America	66.45	−145.55	115	5	Anderson et al. (2018)
LRN 326	Wabamun	North America	53.50	-114.24	732	1	Harrison and Metcalfe (1985)

LRN 327	Weber	North America	47.47	-91.66	559	4	Harrison (1989)
LRN 328	Wedge	North America	50.87	-115.15	1500	1	Harrison and Metcalfe (1985)
LRN 329	White Pond	North America	34.17	-80.78	90	4	Harrison (1989)
LRN 330	White*	North America	33.94	-102.77	1158	MI	Harrison and Metcalfe (1985)
LRN 331	Wintergreen	North America	42.40	-85.38	271	4	Harrison (1989)
LRN 332	Zuni Salt Lake*	North America	34.45	-108.77	1935	MI	Harrison and Metcalfe (1985)
LRN 333	Beatties Tarn	Oceania	-42.67	146.64	90	3	Harrison (1993)
LRN 334	Breadalbane	Oceania	-34.78	149.48	697	4	Harrison (1993)
LRN 335	Bromfield Swamp	Oceania	-17.38	145.54	755	4	Harrison (1993)
LRN 336	Cobrico Swamp	Oceania	-38.31	143.00	80	3	Harrison (1993)
LRN 337	Crown Lagoon	Oceania	-42.29	147.64	375	4	Harrison (1993)
LRN 338	Eagle Tarn	Oceania	-42.68	146.59	4033	4	Harrison (1993)
LRN 339	Kow Swamp	Oceania	-36.00	144.29	83	3	Harrison (1993)
LRN 340	Lake Albacutya	Oceania	-35.75	141.97	90	3	Harrison (1993)
LRN 341	Lake Bancannia	Oceania	-30.82	141.88	107	3	Harrison (1989)
LRN 342	Lake Bullenmerri	Oceania	-38.25	143.12	146	3	Harrison (1993)

LRN 343	Lake Colongulac	Oceania	-38.17	143.17	65	3	Harrison (1993)
LRN 344	Lake Corangamite	Oceania	-38.11	143.5	117	3	Harrison (1993)
LRN 345	Lake Dobson	Oceania	-42.68	146.59	1030	3	Rees et al. (2015)
LRN 346	Lake Euramoo	Oceania	-17.16	145.63	730	4	Harrison (1993)
LRN 347	Lake Eyre	Oceania	-28.50	137.25	-15	3	Harrison (1993)
LRN 348	Lake Frome	Oceania	-30.75	139.83	-2	3	Harrison (1993)
LRN 349	Lake George	Oceania	-35.08	149.42	673	4	Harrison (1993)
LRN 350	Lake Gnotuk	Oceania	-38.23	143.10	102	4	Harrison (1993)
LRN 351	Lake Grace	Oceania	-33.30	118.40	200	3	Harrison (1993)
LRN 352	Lake Keilambete	Oceania	-38.20	142.87	150	3	Harrison (1993)
LRN 353	Lake King	Oceania	-33.08	119.53	350	3	Harrison (1993)
LRN 354	Lake Leake	Oceania	-37.62	140.59	97	4	Harrison (1993)
LRN 355	Lake Tyrrell	Oceania	-35.33	142.78	42	3	Harrison (1993)
LRN 356	Lake Vera	Oceania	-42.74	145.88	560	4	Harrison (1993)
LRN 357	Lake Victoria	Oceania	-34.00	141.28	52	3	Harrison (1993)
LRN 358	Lake Wanum	Oceania	-6.63	146.78	35	3	Harrison (1993)

LRN 359	Lake Tiberias	Oceania	-42.42	147.37	442	3	Harrison (1993)
LRN 360	Lynch's Crater	Oceania	-17.37	145.69	760	4	Harrison (1993)
LRN 361	Myalup Swamp	Oceania	-33.12	115.72	6	3	Harrison (1993)
LRN 362	Quincan Crater	Oceania	-17.30	145.58	790	4	Harrison (1993)
LRN 363	Salt Lake	Oceania	-30.05	142.14	78	3	Harrison (1993)
LRN 364	Storeys Lake	Oceania	-31.52	118.03	300	3	Harrison (1993)
LRN 365	Tysons Lake	Oceania	-33.84	143.84	350	3	Harrison (1993)
LRN 366	Valley Lake	Oceania	-37.84	140.77	100	3	Harrison (1993)
LRN 367	Blanca Lake	South America	8.34	-71.79	1620	1	Bradley et al. (1985)
LRN 368	Brava Lake	South America	8.31	-71.84	2394	1	Bradley et al. (1985)
LRN 369	Caracarana Lake	South America	3.84	-59.78	104	1	Turcq et al. (2002)
LRN 370	Carajás Lake	South America	-6.09	-49.84	680	1	Turcq et al. (2002)
LRN 371	Dom Helvecio Lake	South America	-19.78	-42.59	280	1	Turcq et al. (2002)
LRN 372	El Monton	South America	8.68	-70.88	3683	1	Bradley et al. (1985)
LRN 373	Feia Lake	South America	-15.57	-47.31	855	1	Cassino et al. (2020); Turcq et al. (2002)
LRN 374	Figueirinha Lake	South America	-28.63	-48.93	0**	5	Carvalho do Amaral et al. (2012)

LRN 375	Fuquene	South America	5.48	-73.75	2580	1	Harrison and Metcalfe (1985)
LRN 376	Lago Aleixo	South America	-17.98	-42.11	390	5	Enters et al. (2010)
LRN 377	Lago Castor	South America	-45.59	-71.77	699**	5	Elbert et al. (2013); Fiers et al. (2019)
LRN 378	Lago Chungara	South America	-18.25	-69.10	4520	4	Moreno et al. (2007)
LRN 379	Lago Galvarne Bog	South America	-54.74	-64.32	2	4	Unkel et al. (2008; 2010)
LRN 380	Lagoa do Caçò	South America	-2.58	-43.25	100	4	Boussafir et al. (2012); Pessenda et al. (2005)
LRN 381	Lagoa dos Patos	South America	-31.33	-51.22	-6**	3	Toldo et al. (2000)
LRN 382	Laguna Cascada	South America	-54.76	-64.33	14**	4	Fernandez et al. (2013)
LRN 383	Laguna Ciega	South America	6.54	-72.32	4000	1	Harrison and Metcalfe (1985)
LRN 384	Laguna de Los Anteojos	South America	83.22	-71.42	3920	4	Stansell et al. (2010)
LRN 385	Laguna Escondida	South America	-45.53	-71.82	692**	4	Elbert et al. (2013)
LRN 386	Laguna Jahuacocha	South America	-10.23	-76.96	4076	5	Stansell et al. (2013)
LRN 387	Laguna La Gaiba	South America	-17.75	-57.71	95	5	Metcalfe et al. (2014); Whitney et al. (2011)
LRN 388	Laguna Lutacocha	South America	-10.55	-76.72	4320	5	Stansell et al. (2013)

LRN 389	Laguna Potrok Aike	South America	-51.96	-70.37	112**	4	Haberzettl et al. (2007; 2009); Jouve et al. (2013)
LRN 390	Laguna Queshquecocha	South America	-9.48	-77.18	4260	5	Stansell et al. (2013)
LRN 391	Laguna Yema	South America	-24.35	-61.33	154**	4	Speranza et al. (2019)
LRN 392	Lake Boqueirão	South America	-5.25	-35.55	17	5	Gomes et al. (2014); Utida et al. (2019); Viana et al. (2014); Zocatelli et al. (2012); Zular et al. (2018)
LRN 393	Lake Calafquén	South America	-39.52	-72.14	204	4	Van Daele et al. (2014)
LRN 394	Lake Canto Grande	South America	-19.26	-39.94	5	5	Lorente et al. (2018)
LRN 395	Lake Chiquita	South America	-30.90	-62.85	67	2	Horton et al. (2016)
LRN 396	Lake Junin	South America	-11.02	-76.12	4082	2	Horton et al. (2016)
LRN 397	Lake Melincué	South America	-33.70	-61.47	84**	4	Guerra et al. (2015; 2017)
LRN 398	Lake Pastahué	South America	-42.37	-73.83	150	4	Castro et el. (2019)
LRN 399	Lake Pumacocha	South America	-11.89	-75.05	4635	2	Horton et al. (2016)
LRN 400	Lake Salina da Ponta	South America	-18.98	-56.66	100**	1	Becker et al. (2018)
LRN 401	Lake Villarica	South America	-39.24	-72.09	214	4	Van Daele et al. (2014)

LRN 402	Lirios Lake	South America	8.31	-71.83	2299	1	Bradley et al. (1985)
LRN 403	Mucubaji Lake	South America	8.79	-70.83	3565	1	Bradley et al. (1985)
LRN 404	Negra Lake	South America	8.78	-70.81	3470	1	Bradley et al. (1985)
LRN 405	Preta de Baixo Lake	South America	-18.42	-41.85	470	1	Turcq et al. (2002)
LRN 406	Saisay Lake	South America	8.73	-70.84	3747	1	Bradley et al. (1985)
LRN 407	Solimões River	South America	-4.35	-69.9	70	1	Kern et al. (2020)
LRN 408	Tapajós Lake	South America	-2.78	-55.08	1	5	Irion et al. (2006); Turcq et al. (2002)
LRN 409	Urao Lake	South America	8.50	-71.40	1024	1	Bradley et al. (1985)
LRN 410	Valencia	South America	10.1	-67.75	402	1	Harrison and Metcalfe (1985)

* articles that did not contain all the information considered. **estimated data (See Section 2 for more detail). MI: Missing Information. P states for Types of proxy: 1. Biological proxies, 2. Isotopic ratio proxies, 3. Physicochemical proxies, 4. Two types of proxy and 5. Three types of proxy/Multiproxy approach.

Table 2. Absolute and relative number of lakes used in this study according to location.

Continent	**Number of lakes**	**Percentage**
Africa	67	16%
Asia	56	14%
Central America	3	1%
Europe	103	25%
North America	103	25%
Oceania	34	8%
South America	44	11%
Total	410	100%

Table 3. Amount of lakes according to the type of proxy and continent.

P	MI	1	2	3	4	5	Total number of lakes
Africa	0	58	1	0	4	4	67
Asia	0	8	10	9	21	8	56
Central America	0	0	1	0	2	0	3
Europe	0	43	2	9	37	12	103
North America	29	13	20	12	23	6	103
Oceania	0	0	0	23	11	0	34
South America	0	18	3	1	12	10	44
Total	29	140	37	54	110	40	410
Percentage	7%	34%	10%	13%	27%	9%	100%

Type of proxy (P): MI. Missing Information, 1. Biological proxies, 2. Isotopic ratio proxies, 3. Physicochemical proxies, 4. Two types of proxy and 5. Three types of proxy/Multiproxy approach.

Table 4. Amount of lakes according to their altitude.

Altitude	Total Number of Lakes
<0m	11
0-1000m	258
1001-2000m	84
2001-3000m	16
3001-4000m	16
4001-5000m	19
>5000m	3
M.I.*	3
Total	410

*M.I. Missing Information

Table 5. Description of the proxy types used in this study (Modified from Prado et al., 2013).

Proxy Type	Description	Specification
Biological	Diatom Analysis	Type and quantitative analysis
	Organic Matter	TOC, TIC, TN, TOC/TN, C/N
	Pollen Analysis	Type and quantitative analysis
Isotopic ratio	$\delta^{13}C$	$^{13}C/^{12}C$
	$\delta^{15}N$	$^{15}N/^{14}N$
	$\delta^{18}O$	$^{18}O/^{16}O$
Physicochemical	Elemental Analysis and Inorganic Ratios	Al, Al/Ca, Al/Si, Br, Ca, Ca/Al, Ca/Fe, Ca/Si, Ca/Ti, Ca/Σ(Ti, Fe, Al), Cu/Rb, Fe, Fe/Al, Fe/K, Fe/Mn, Fe/Si, Fe/Ti, K, K/Al, K/Ti, Mg, Mg/Ca, Mn, Mn/Fe, Mn/Ti, Nb/Ti, P, Pb, Rb, Rb/K, Rb/Sr, S, S/Ti, Si, Si/Ti, Si/Zr, Sr, Sr/Ca, Sr/Rb, Sr/Ti, Th, Ti, Ti/Ca, Ti/K, Zr, Zr/Fe, Zr/K, Zr/Rb, Zr/Ti
	Environmental Magnetism	X, χlf, χhf, χfd%, χARM, SIRM, HIRM, S Ratio, ARM/SIRM, ARM/χ, χ_{ARM}/χ_{lf}, χ_{ARM}/SIRM, SIRM/ χlf
	Grain Size Analysis	Particle size analysis

Table 6. The organic matter parameters and their information and environmental interpretation. This summary is based on the site-specific context, and that can not necessarily be extrapolated to other lakes.

Parameter	**Parameters information**	**Environmental interpretation (higher values)**	**Example reference**
Total Organic Carbon (TOC)	Amount of organic matter	Increase contribution from plankton that can indicate high rainfall	Katsuta et al. (2017); Meyers and Lallier-Verges (1999)
		High lake level, that can indicate high rainfall	Guerra et al. (2017); Viana et al. (2014); Turcq et al. (2002)
Total Inorganic Carbon (TIC)	Associated to evaporitic, endogenic or biogenic carbonates	High alkalinity and salinity conditions	Burnett et al. (2011); Martín-Puertas et al. (2011)
Total Nitrogen (TN)	Terrestrial or lacustrine origin of the organic matter	Enhanced plankton productivity at high lake levels, that can indicate high rainfall	Guerra et al. (2017)
TOC/TN	Terrestrial or lacustrine origin of the organic matter	Low primary productivity and predominant detrital organic matter sources	Meyers (1994, 2003)

Carbon/Nitrogen (C/N)	Proportions of terrestrial or lacustrine organic matter	Higher contribution of aquatic macrophytes or terrestrial plants, that can indicate low rainfall	Díaz et al. (2017); Metcalfe et al. (2014); Viana et al. (2014)
		Low lake level, that can indicate low rainfall	Meyers and Lallier-Verges (1999); Rühland et al (2009); Viana et al. (2014)

Table 7. $\delta^{13}C$ environmental interpretation according to the dominant source. This summary is based on the site-specific context, and that can not necessarily be extrapolated to other lakes.

Dominant Source	**Terrestrial**	**Aquatic**	**Environmental interpretation**	**Example location**	**Example reference**
More negative $\delta^{13}C$	Indicates greater proportion of C3 vegetation	May indicate decreased algal productivity	Wet conditions	Lake Tanganyika	Burnett et al. (2011)
				Lake Bolgoda	Gayantha et al. (2017)
				Ziro Lake	Gosh et al. (2014)
				Shantisagara Lake	Sandeep et al. (2017)
			Cooler conditions	Fallen Leaf Lake	Noble et al. (2016)
Less negative $\delta^{13}C$	Indicates greater proportion of C4 vegetation	May indicate increased algal productivity, causing an enrichment in the carbon pool	Dry conditions	Lake Tanganyika	Burnett et al. (2011)
				Lake Bolgoda	Gayantha et al. (2017)
				Shantisagara Lake	Sandeep et al. (2017)

Table 8. The main indicator/use and environmental interpretation associated with the amount of $\delta^{15}N$. This summary is based on the site-specific context, and that can not necessarily be extrapolated to other lakes.

$\delta^{15}N$	Indicator/use	Environmental interpretation	Example location	Example reference
High	More phytoplankton contribution	High lake level; wet periods	Lake Bolgoda	Gayantha et al. (2017)
			Fallen Leaf Lake	Noble et al. (2016)
			Lake Boqueirão	Viana et al. (2014)
	Higher primary production		Lake Bosumtwi	Talbot and Johannessen (1992)
Low	Column stratification and limited vertical DIN cycling	Low lake level; dry periods	Mono Lake	Hodelka et al. (2020)
	More atmospheric nitrogen contribution		Lake SS85	Olsen et al., (2013)

Table 9. $\delta^{18}O$ and environmental interpretation associated. This summary is based on the site-specific context, and that can not necessarily be extrapolated to other lakes.

$\delta^{18}O$	**Environmental interpretatic**	**Example location**	**Example reference**
High	Warm periods	Lake Bled	Andrič et al. (2009)
		Lake Ocotalito	Díaz et al. (2017)
		Lake Mondsee	Lauterbach et al. (2011)
		Lake Van	Litt et al. (2009)
		Lake Lautrey	Magny et al. (2006)
	Dry conditions	Lake Petén Itzá	Grauel et al. (2016)
Low	Cold conditions	Lake Bled	Andrič et al. (2009)
	Humid conditions	Lake Ocotalito	Díaz et al. (2017)

Table 10. Elements and ratios used as process and environmental proxies in lake sediments and their basic indicator/use. This summary is based on the site-specific context, and that can not necessarily be extrapolated to other lakes.

Element or Ratio	Indicator/use	Reference
Al	Variations in terrigenous sediment delivery	Kämpf et al. (2012); Lauterbach et al. (2011); Lopez et al. (2006); Metcalfe et al. (2014)
Al/Ca	Terrigenous input variability	Tardy et al. (2004)
Al/Si	Transport (wind and hydrodynamic) and weathering	López et al. (2006); Van Daele et al. (2014)
Br	Organic matter and biological productivity	Fedotov et al. (2012); Kalugin et al. (2007, 2013); Unkel et al. (2010)
Ca	Mixed signal of detrital flow and authigenic precipitation in lake waters	Balascio et al. (2011); Brown (2011); Cohen, A. S. (2003); Cuven et al. (2011); Elbert et al. (2013); Foerster et al. (2012); Lauterbach et al. (2011); Marshall et al. (2011); Scholz et al. (2007); Wünnemann et al. (2010)
Ca/Al	Related to water mineralization (e.g. due to the high solubility of calcite), or chemical weathering	López et al. (2006); Tardy et al. (2004)

Ca/Fe	Variation in terrigenous sediment delivery	Elbert et al. (2013)
Ca/Mg	Biochemical calcite precipitation and water mineralization	Lauterbach et al. (2011); López et al. (2006)
Ca/Si	Water temperature change and authigenic precipitation	Jouve et al. (2013); Wünnemann et al. (2010)
Ca/Ti	Information about erosion in the catchment, annual or seasonal precipitation and fluvial/eolian transport versus carbonate production and productivity of the lake	Haberzettl et al. (2007, 2009); Jouve et al. (2013); Kylander et al. (2011); Litt et al. (2009); Metcalfe et al. (2014); Olsen et al. (2013)
Ca/ΣTi, Fe, Al	Authigenic carbonate precipitation	Mueller et al. (2009)
Cu/Rb	Mining pollution	Guyard et al. 2007
Fe	Terrigenous sediment inputs, redox conditions and volcanic debris and tephra indicator	Chao et al. (2009); Cuven et al. (2010); Davison (1993); Kylander et al. (2011); Kylander et al. (2012); Van Daele et al. (2014)
Fe/Al	Redox conditions	López et al. (2006)
Fe/K	Terrigenous sediment input	Metcalfe et al. (2014)
Fe/Mn	Redox conditions	Corella et al. (2012); Cuven et al. (2011); Haberzettl et al. (2007)

Fe/Si	Volcanic sediments	Van Daele et al. (2014)
Fe/Ti	Redox conditions and sediments grain size	Aufgebauer et al. (2012); Marshall et al. (2011)
K	Terrigenous sediment input, weathering and tephra	Aufgebauer et al. (2012); Chao et al. (2009); Cuven et al. (2010); Foerster et al. (2012); Kämpf et al. (2012); Kylander et al. (2011, 2012); Moreno et al. (2011); Vogel et al. (2010)
K/Al	Weathering	Burnett et al. (2011)
K/Ti	Weathering	Arnaud et al. (2012); Cuven et al. (2010)
Mg	Terrigenous sediment input	Chao et al. (2009); Lauterbach et al. (2011)
Mg/Ca	Authigenic carbonate precipitation	Martin-Puertas et al. (2011)
Mn	Terrigenous sediment input, water oxygenation and tephra	Chao et al. (2009); Marshall et al. (2012); Moreno et al. (2008); Kylander et al. (2011, 2012)
Mn/Fe	Redox conditions	Burn and Palmer (2014); López et al. (2006); Melles et al. (2012); Unkel et al. (2008)

Mn/Ti	Redox conditions	Kylander et al. (2011); Moreno et al. (2007)
Nb/Ti	Erosion of magma intrusion	Shala et al. 2014
P	Nutrient content	Corella et al. (2012); López et al. (2006)
Pb	Mining pollution	Guyard et al. (2007)
Rb	Terrigenous sediment inputs, grain size and tephra	Damaschke et al. (2013); Guyard et al. (2007); Kalugin et al. (2013); Kylander et al. (2011); Miller et al. (2014)
Rb/K	Weathering	Brown (2011); Burnett et al. (2011)
Rb/Sr	Weathering	Fernandez et al. (2013); Unkel et al. (2010)
S	Leaching, marine influence and evaporative concentration	Balascio et al. (2011); Burn and Palmer (2014); Burnett et al. (2011); Hodell et al. (2012); Olsen et al. (2013)
S/Ti	Organic matter	Moreno et al. (2007)
Si	Variation in terrigenous sediment delivery and sediment grain size	Cuven et al. (2010); Kämpf et al. (2012); Kylander et al. (2011); Martin-Puertas et al.

		(2011); Marshall et al. (2011); Moreno et al. (2011)
Si/Ti	Biogenic silica content and sediment grain size	Brown et al. (2007); Brown (2011); Burnett et al. (2011); Balascio et al. (2011); Kylander et al. (2011); Martin-Puertas et al. (2012); Melles et al. (2012); Stansell et al. (2010); Shala et al. (2014)
Si/Zr	Biogenic silica content Vs detrital material	Cuven et al. (2011)
Sr	Weathering, erosion, $SrCO_3$ precipitation and tephra	Burn and Palmer (2014); Stansell et al. (2013); Vogel et al. (2010)
Sr/Ca	Authigenic carbonate	Martin-Puertas et al. (2011)
Sr/Rb	Unweathered terrestrial fraction	Fedotov et al. (2012); Kalugin et al. (2007)
Sr/Ti	$SrCO_3$ precipitation and silt influx	Kylander et al. (2011); Moreno et al. (2007); Shala et al. (2014)
Th	Permafrost defrosting and leaching	Fedotov et al. (2012)

Ti	Terrigenous sediment input	Bakke et al. (2009); Balascio et al. (2011); Berntsson et al. (2014); Corella et al. (2012); Cuven et al. (2010); Czymzik et al. (2013); Kylander et al. (2011, 2012); Martin-Puertas et al. (2012); Metcalfe et al. (2010); Peru Stansell et al. (2013); Yancheva et al. (2007)
Ti/Ca	Terrigenous sediment input	Litt et al. (2009)
Ti/K	Grain size	Marshall et al. (2011)
Zr	Grain size, erosion and tephra	Cuven et al. 2010; Marshall et al. (2011); Vogel et al. (2010); Stansell et al. (2013)
Zr/Fe	Grain size	Wilhelm et al. (2013)
Zr/K	Grain size	Cuven et al. (2011)
Zr/Rb	Grain size	Chawchai et al. (2013); Dypvik and Harris (2001); Kylander et al. (2011)
Zr/Ti	Volcanic sediments	Brown et al. (2007)

Table 11. Elements and ratios used as process and environmental proxies in lake sediments and their environmental interpretation. For several elements and ratios, there are various interpretations based on the site-specific context, and that can not necessarily be extrapolated to other lakes. This summary is based on the site-specific context, and that can not necessarily be extrapolated to other lakes.

Element or Ratio	Environmental interpretation (higher values)	Example location	Example reference
Al	Flood/detrital layers	Lago Maggiore, Italy	Kämpf et al. (2012)
	Detrital siliclastics (Flysch Zone)	Lake Mondsee, Austria	Lauterbach et al. (2011)
Al/Ca	Great terrigenous input	Niger River, Africa	Tardy et al. (2004)
Al/Si	Fine silt and clay layers	Lake Villarrica, Chile	Van Daele et al. (2014)
Br	Increased biological productivity/organic content	Lake Dalgan, Taimyr Peninsula, Siberia	Fedotov et al. (2012)
	Increased organic content	Shira Lake, Siberia	Kalugin et al. (2013)
		Lake Teletskoye, Siberia	Kalugin et al. (2007)
	Sea spray/increased storminess	Isla de los Estados, Tierra del Fuego	Unkel et al. (2010)

Ca	Increased calcite precipitation/ Evaporative concentration	Lake Malawi, eastern Africa	Scholz et al. (2007); Brown (2011)
		Lake Tana, Ethiopia	Marshall et al. (2011)
	Endogenic calcite production + detrital carbonates	Chew Bahir, Ethiopia	Foerster et al. (2012)
	Increased primary productivity	Lake Mondsee, Austria	Lauterbach et al. (2011)
	Increased marine influence	East Lake, Cape Bounty, Canada	Cuven et al. (2011)
	Increased allochthonous Lithoclastic material	Heimerdalsvatnet, Lofoten, Norway	Balascio et al. (2011)
	Tephra	Lago Castor/Laguna Escondida, Chile	Elbert et al. (2013)
Ca/Al	Higher conductivity mainly related with water Mineralization	24 reservoirs at Iberian Peninsula	López et al. (2006)
		Niger River, Africa	Tardy et al. (2004)
Ca/Fe	Increased pedogenic input	Lago Castor/Laguna Escondida, Chile	Elbert et al. (2013)
Ca/Mg	Biochemical calcite precipitation	Lake Mondsee, Austria	Lauterbach et al. (2011)

	Higher conductivity mainly related with water mineralization	24 reservoirs at Iberian Peninsula	López et al. (2006)
Ca/Si	Water temperature change, either colder due to presence of calcite derived from ikaite or warmer due to association with green alga *Phacotus lenticularis*	Lake Potrok Aike, Argentina	Jouve et al. (2013)
	Increased authigenic precipitation	Tso Kar lake basin, northwestern Himalayas	Wünnemann et al. (2010)
Ca/Ti	Increased evaporative concentration	Lake Potrok Aike, Argentina	Haberzettl et al. (2007, 2009); Jouve et al. (2013)
		Laguna La Gaiba, Bolivia/Brazil	Metcalfe et al. (2014)
	In-lake carbonate precipitation	Les Echets, France	Kylander et al. (2011)
		Lake Van, Turkey	Litt et al. (2009)
	Biologically mediated calcite production	Southwest Greenland	Olsen et al. (2013)

Ca/ΣTi, Fe, Al	Increased authigenic carbonate precipitation (drier conditions)	Lake Peten Itzá, Guatemala	Mueller et al. (2009)
Cu/Rb	High copper pollution	Lake Bramant, French Alps	Guyard et al. (2007)
Fe	Clay rich layers in varved sediment	Cape Bounty, Canada	Cuven et al. (2010)
	Detrital inputs, redox conditions (non-stationarity)	Les Echets, France	Kylander et al. (2011)
		Lop Nur, China	Chao et al. (2009)
	Fine silt, clay of volcanic origin	Lake Villarrica, Chile	Van Daele et al. (2014)
	Tephra	Faroe Islands	Kylander et al. (2012)
Fe/Al	Reducing conditions	24 reservoirs at Iberian Peninsula	López et al. (2006)
Fe/K	Detrital inputs	Laguna La Gaiba, Bolivia/Brazil	Metcalfe et al. (2014)
Fe/Mn	Reducing conditions	Lake Montcortès	Corella et al. (2012)
		East Lake, Cape Bounty, Canada	Cuven et al. (2011)
		Lake Potrok Aike	Haberzettl et al. (2007)
Fe/Si	Fine silt and clay, volcanic origin	Lake Villarrica, Chile	Van Daele et al. (2014)
Fe/Ti	Reducing conditions	Lake Prespa, Balkan Peninsula	Aufgebauer et al. (2012)

	Reduction in grain-size	Lake Tana, Ethiopia	Marshall et al. (2011)
K	Increased detrital input	Lake Prespa, Balkan Peninsula	Aufgebauer et al. (2012)
		Lago Enol	Moreno et al. (2011)
		Lop Nur, China	Chao et al. (2009)
	Flood layers	Lago Maggiore	Kämpf et al. (2012)
	Drier conditions (physical > chemical weathering)	Chew Bahir, Ethiopia	Foerster et al. (2012)
	Clay rich layers in varved sediments	Cape Bounty, Canada	Cuven et al. (2010)
	Fine-grained detrital inputs	Les Echets, France	Kylander et al. (2011)
	Tephra	Lake Ohrid, Balkans	Vogel et al. (2010)
		Faroe Islands	Kylander et al. (2012)
K/Al	Illite/kaolinite ratio (physical > chemical weathering)	Lake Tanganyika, eastern Africa	Burnett et al. (2011)
K/Ti	Increased physical relative to chemical weathering	Lake Bourget, France	Arnaud et al. (2012)
	Identification of upper varve boundary	Cape Bounty, Canada	Cuven et al. (2010)
Mg	Detrital dolomite	Lake Mondsee	Lauterbach et al. (2011)

		Lop Nur, China	Chao et al. (2009)
Mg/Ca	Intense authigenic carbonate precipitation	Zoñar Lake, Spain	Martin-Puertas et al. (2011)
Mn	Detrital inputs	Lake Taravilla, Spain	Moreno et al. (2008)
	Mn-enriched siderite layers	Lake Suigetsu	Marshall et al. (2012)
	Oxygenation of bottom waters (lower lake level)	Les Echets, France	Kylander et al. (2011)
	Tephra	Faroe Islands	Kylander et al. (2012)
Mn/Fe	Oxygenation of water column	El-gygytgyn, Siberia	Melles et al. (2012)
	Oxyc conditions	Albion Ponds, Jamaica	Burn and Palmer (2014)
		Lago Galvarne Bog, Tierra del Fuego	Unkel et al. (2008)
Mn/Ti	Oxygenation of water column	Lake Chungara, Chile	Moreno et al. (2007)
		Les Echets, France	Kylander et al. (2011)
Nb/Ti	Erosion of carbonate rich magma intrusion	Lake Loitsana, Finland	Shala et al. (2014)
P	Nutrient enrichment	Lake Montcortès, Spain	Corella et al. (2012)
Pb	Pollution from mining	Lake Bramant, France	Guyard et al. (2007)

		Lake Windermere, UK	Miller et al. (2014)
Rb	Detrital inputs	Shira Lake, Siberia	Kalugin et al. (2013)
	Fine-grained detrital inputs	Les Echets, France	Kylander et al. (2011)
	Tephra	Lake Bramant, France	Guyard et al. (2007)
		Lake Prespa, Balkans	Damaschke et al. (2013)
Rb/K	Increased chemical weathering	Lake Malawi, eastern Africa	Brown (2011)
		Lake Tanganyika, eastern Africa	Burnett et al. (2011)
Rb/Sr	Increased chemical weathering	Laguna Cascada, Isla de los Estados, Tierra del Fuego	Fernandez et al. (2013); Unkel et al. (2010)
S	Increased marine influence	Heimerdalsvatnet, Lofoten, Norway	Balascio et al. (2011)
	Gypsum precipitation (evaporative concentration)	Albion Ponds, Jamaica	Burn and Palmer (2014)
	Soil derived S from leaching	Lake Tanganyika, eastern Africa	Burnett et al. (2011)
		Lake Petén Itzá, Guatemala	Hodell et al. (2012)
		Southwest Greenland	Olsen et al. (2013)

S/Ti	Presence of pyrite, increased organic matter	Lake Chungara, Chile	Moreno et al. (2007)
Si	Coarse silt and sand	Cape Bounty, Canada	Cuven et al. (2010)
	Flood layers	Lago Maggiore, Italy	Kämpf et al. (2012)
	Increased detrital inputs	Zoñar Lake, Spain	Martin-Puertas et al. (2011)
		Lake Tana, Ethiopia	Marshall et al. (2011)
		Les Echets, France	Kylander et al. (2011)
	Increased clay and quartz content	Lago Enol, Spain	Moreno et al. (2011)
Si/Ti	Increased biogenic silica (principally diatoms)	Lake Malawi, eastern Africa	Brown et al. (2007); Brown (2011)
		Lake Tanganyika, eastern Africa	Burnett et al. (2011)
		Heimerdalsvatnet, Lofoten, Norway	Balascio et al. (2011)
		Les Echets, France	Kylander et al. (2011)
		Meerfelder Maar	Martin-Puertas et al. (2012)
		El’gygytgyn, Siberia	Melles et al. (2012)

		Laguna de Los Anteojos, Venezuela	Stansell et al. (2010)
	Grain-size (sand)	Lake Loitsana, Finland	Shala et al. (2014)
Si/Zr	High biogenic silica content relative to detrital material	East Lake, Cape Bounty, Canada	Cuven et al. (2011)
Sr	In-lake $SrCO_3$ precipitation	Albion Ponds, Jamaica	Burn and Palmer (2014)
	Erosion of granodiorite	Laguna Queshquecocha	Stansell et al. (2013)
	Tephra	Lake Ohrid, Balkans	Vogel et al. (2010)
Sr/Ca	Authigenic carbonate precipitation	Zoñar Lake, Spain	Martin-Puertas et al. (2011)
Sr/Rb	Unweathered terrestrial fraction	Taimyr Peninsula, Siberia	Fedotov et al. (2012)
		Teletskoye Lake, Siberia	Kalugin et al. (2007)
Sr/Ti	In-lake $SrCO_3$ precipitation	Les Echets, France	Kylander et al. (2011)
		Lake Chungara, Chile	Moreno et al. (2007)
	Silt influx	Lake Loitsana, Finland	Shala et al. (2014)

Th	Leaching of Th from soil during thawing of permafrost	Taimyr Peninsula, Siberia	Fedotov et al. (2012)
Ti	Increased run-off/rainfall	Laguna de Juanacatlan, Mexico	Metcalfe et al. (2010)
		Lake Montcortès, Spain	Corella et al. (2012)
	Increased detrital input	Heimerdalsvatnet, Lofoten, Norway	Balascio et al. (2011)
	Detrital input (glacier advance)	Laguna Lutacocha, Peru	Stansell et al. (2013)
	Fine grained detrital input	Meerfelder Maar, Germany	Martin-Puertas et al. (2012)
	Increased inwash of silt	Les Echets, France	Kylander et al. (2011)
	Identification of flood layers	Lake Vuoksjávrátje, Sweden	Berntsson et al. (2014)
	Increased glacial meltwater	Lake Ammersee, Switzerland	Czymzik et al. (2013)
	Increased aeolian deposition	Lake Kråkenes, Norway	Bakke et al. (2009)
	Silt-rich facies	Huguang Maar, China	Yancheva et al. (2007)
	Clay-rich sediment	Cape Bounty, Canada	Cuven et al. (2010)
	Tephra	Faroe Islands	Kylander et al. (2012)

Ti/Ca	Increased detrital input	Lake Van, Turkey	Litt et al. (2009)
Ti/K	Increased grain-size	Lake Tana, Ethiopia	Marshall et al. (2011)
Zr	Coarse silt and sand	Cape Bounty, Canada	Cuven et al. (2010)
	Detrital inputs	Lake Tana, Ethiopia	Marshall et al. (2011)
	Tephra	Lake Ohrid, Balkans	Vogel et al. (2010)
	Erosion of metasediments	Laguna Queshquecocha	Stansell et al. (2013)
Zr/Fe	Flood layers/grain-size	Lake Blanc, France	Wilhelm et al. (2013)
Zr/K	Coarser grain-size	East Lake, Cape Bounty, Canada	Cuven et al. (2011)
Zr/Rb	Coarser grain-size	Lake Kumphawapi, Thailand	Chawchai et al. (2013)
		Les Echets, France	Kylander et al. (2011)
Zr/Ti	Weathered volcanic ash (catchment inwash)	Lake Malawi, eastern Africa	Brown et al. (2007)

Table 12. The mineral magnetic parameters and their basic interpretation. This summary is based on the site-specific context, and that can not necessarily be extrapolated to other lakes.

Magnetic parameters and ratios	**Interpretation of magnetic mineral parameters**	**Environmental interpretation (higher values)**	**References**
Magnetic susceptibility (χ)	Indicate the total concentration of magnetic minerals present in a natural sample. Is influenced by geochemical and detrital processes	More magnetic minerals, which may indicate wetter periods	Basavaiah et al. (2015); Walden et al. (1999)
Low frequency magnetic susceptibility (χlf)	Is proportional to the magnetic mineral concentration. Ferrimagnetic minerals or superparamegnetic grains usually dominate the signal	Intensive catchment erosion due to high rainfall or sparse vegetation coverage	Sandeep et al. (2017); Wei et al. (2018) *
High frequency magnetic susceptibility (χhf)	Is proportional to the magnetic mineral concentration	Cautious catchment erosion due to low rainfall	Mehrotra et al. (2019)

Frequency dependent relative magnetic susceptibility (χfd%)	Reflects percentage of ferrimagnetic superparamagnetic grains in total magnetic minerals	Large amounts of supermagnetic minerals and fine-grained magnetic minerals	Dearing (1999a); Dearing et al. (1996)
Anhysteretic susceptibility (χARM)	Reflects the concentrations of ferrimagnetic minerals. Is based on the finer grains. Baised towards stable single domain magnetic minerals	Greater influx of pedogenic magnetite by sediment uptake, which may indicate wetter periods	Mahe (1988); Wei et al. (2018) *
Soft isothermal remanent magnetization (SIRM)	It is proportional to the concentration of minerals with remanent magnetism	Higher amount of magnetic minerals except paramagnetic minerals	Walden et al. (1999); Wei et al. (2018) *
Hard isothermal remanent magnetization (HIRM)	It is indicative of the relative ratio of antiferromagnetic to ferrimagnetic minerals	Greater amount of antiferromagnetic minerals	Rawat et al. (2015a); Thompson and Oldfield (1986)

S Ratio	It is indicative of the relative proportions of ferromagnetic and antiferromagnetic minerals	Higher amount of low coercivity ferrimagnetic minerals, such as magnetite and maghemite	Evans and Heller (2003); Thompson and Oldfield (1986); Walden et al. (1999)
ARM/SIRM and ARM/χ	It is indicative of the size and the type of the magnetic grains	Smaller grain size ang higher proportion of SD grains, which may indicate less rainy periods	Hunt et al. (1995)
χ_{ARM}/χ_{lf} and χ_{ARM}/SIRM	It is indicative of the size of the magnetic grains	Fine magnetic grain size, which may indicate less rainy periods	Björck et al. (2006); Oldfield (1991)
SIRM/ χlf	It is used to support the existence of authigenic magnetite	Reducing conditions in the lake	Wei et al. (2018) *

*Further information in the main text.

Table 13. Grain size and their environmental interpretation associated. This summary is based on the site-specific context, and that can not necessarily be extrapolated to other lakes.

Grain size	Environmental interpretation	Example reference
Sand	High rainfall	Bali et al. (2017); Bhattacharyya et al. (2015); Sandeep et al. (2017)
Fluctuating percentages of sand and clay or silt	Variation of rainfall periods	Guerra et al. (2017)
Clay/Silt	Low rainfall	Bali et al. (2017); Sandeep et al. (2017)
	Relatively deeper and calm environment	Babeesh et al. (2019); Mishra et al. (2019)

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Appendix II

II.I. Tables of the item 3.2. ^{14}C Age Calibration

Table 14. Compiled records that had their ^{14}C age models calibrated in this study.

Core Code	Core Name	Site Name	Lat (°)	Long (°)	Reference
0001	LC3	Salitre de Minas	-19.00	-46.77	Ledru (1993)
0002	Morro de Itapeva	Morro de Itapeva	-22.78	-45.53	Behling (1997a)
0004	Fazenda do Pinto	São Francisdo de Paula	-29.24	-50.57	Behling et al. (2001a)
0005	Jacareí Peat	Jacareí Peat	-23.28	-45.97	Garcia et al. (2004)
0007	Volta Velha	Volta Velha	-26.07	-48.63	Behling and Negrelle (2001)
0010	MA-97-1	Lagoa do Caçó	-2.96	-43.42	Ledru et al. (2001)
0016	Saquinho	Saquinho	-10.40	-43.22	de Oliveira et al. (1999)
0017	Serra Campos Gerais	Serra Campos Gerais	-24.40	-50.13	Behling (1997b)
0018	CO-3	Colônia	-23.87	-46.71	Ledru et al. (2009)
0019	Lago do Pires	Lago do Pires	-17.95	-42.22	Behling (1995a)
0020	Águas Claras	Águas Claras	-30.10	-50.85	Bauermman et al. (2003)
0021	Serra da Boa Vista	Serra da Boa Vista	-27.70	-49.15	Behling (1995b)
0022	Morro da Igreja	Morro da Igreja	-28.18	-49.87	Behling (1995b)
0023	Serra do Rio Rastro	Serra do Rio Rastro	-28.38	-49.55	Behling (1995b)
0025	Serra do Araçatuba	Serra do Araçatuba	-25.92	-48.98	Behling (2007)

0026	Cerro do Touro	Cerro do Touro	-26.25	-49.25	de Oliveira et al. (2008a)
0028	Lago do Aquiri	Lago do Aquiri	-3.17	-44.98	Behling and Costa (1997)
0029	LC-B1	Lago Calado	-3.27	-60.58	Behling et al. (2001b)
0031	CSS2	Serra Sul de Carajás	-6.33	-50.42	Absy et al. (1991)
0032	Lake Pata	Lake Pata	0.27	-66.68	Colinvaux et al. (1996)
0035	VAE2	Águas Emendadas	-15.57	-47.58	Barberi et al (2000)
0036	Lagoa da Confusão	Lagoa da Confusão	-10.63	-49.72	Behling et al. (2002b)
0037	LS-1	Lagoa Santa	-19.63	-43.90	Parizzi et al. (1998)
0038	GER	Lake Geral	-1.80	-53.53	Bush et al. (2000)
0044	Lagoa Dourada	Lagoa Dourada	-25.24	-50.04	Moro et al. (2004)
0045	CR1	Cromínia	-17.28	-49.42	Salgado-Laboriau et al. (1997)
0049	Serra Velha	Serra Geral	-29.60	-51.65	Leal andLorscheitter (2007)
0050	Arroyo Souce Chico	Arroyo Souce Chico	-38.08	62.26	Prieto (1996)
0051	Empalme Querandies	Empalme Querandies	-37.00	-61.11	Prieto (1996)
0079	Sonda 2	Taquarussu	-22.50	-52.33	Parolin et al. (2006)
0080	Fazenda Urbano	Buritizeiro	-17.41	-45.06	Lorente et al. (2010)
0081	Fazenda Laçador	Vereda Laçador	-18.81	-45.43	Cassino (2011)
0082	Salitre de Minas	Salitre de Minas	-19.00	-49.77	Passenda et al. (2004a)
0083	Londrina	Londrina	-23.30	-51.17	Passenda et al. (2004a)
0084	Piracicaba	Piracicaba	-22.77	-47.63	Passenda et al. (2004a)

0085	Botucatu	Botucatu	-23.00	-48.00	Passenda et al. (2004a)
0086	Anhembi	Anhembi	-22.75	-47.97	Passenda et al. (2004a)
0087	Jaguariuna	Jaguariuna	-22.67	-47.02	Passenda et al. (2004a)
0088	Salitre de Minas	Salitre de Minas	-19.00	-46.77	Passenda et al. (2004a)
0090	Tamanduá River	Tamanduá River	-21.46	-47.60	Turcq et al. (1997)
0091	CSS2	Carajás	-6.33	-50.42	Servant et al. (1993)
0092	LC3	Salitre de MInas	-19.00	-46.77	Servant et al. (1993)
0093	CSS2	Carajás	-6.58	-49.50	Siffedine et al. (2004)
0096	CSS2	Carajás	-6.58	-49.50	Siffedine et al. (2004)
0097	LDH98-4	Lake Don Helvéquio	-19.67	-42.63	Siffedine et al. (2004)
0099	Paraná River	Paraná River	-22.72	-53.17	Stevaux (2000)
0100	Botucatu I	Botucatu	-23.00	-48.00	Gouveia et al. (2002)
0100	Botucatu II	Botucatu	-23.00	-48.00	Gouveia et al. (2002)
0101	Anhembi	Anhembi	-22.75	-47.97	Gouveia et al. (2002)
0102	Jaguariuna	Jaguariuna	-22.67	-47.02	Gouveia et al. (2002)
0103	Pontes e Lacerda	Pontes e Lacerda	-15.27	-59.22	Gouveia et al. (2002)
0105	Campo Alegre	Campo Alegre	-26.25	-49.25	de Oliveira et al. (2008b)
0112	BOT	Botucatu	-22.85	-48.48	Scheel-Ybert et al. (2003)
0112	BOT	Botucatu	-22.85	-48.48	Scheel-Ybert et al. (2003)
0113	JAG	Jaguariuna	-22.67	-47.17	Scheel-Ybert et al. (2003)

0113	JAG II	Jaguariuna	-22.67	-47.17	Scheel-Ybert et al. (2003)
0114	PIN	Anhembi	-22.75	-47.97	Scheel-Ybert et al. (2003)
0117	Lagoa da Serra Negra	Lagoa Serra	-18.95	-46.83	Oliveira (1992)
0118	Lagoa dos Olhos	Lagoa dos Olhos	-19.38	-43.90	Oliveira (1992)
0119	CR1	Cromínia	-17.28	-49.92	Ferraz-Vicentini and Salgado-Labouriau (1996)
0147	Porto Velho Humaita Km 46	Porto Velho Humaita	-8.00	-63.3	(de Freitas et al., 2017)
0147	Porto Velho Humaita Km 188	Porto Velho Humaita	-9.00	-63.3	(de Freitas et al., 2017)
0148	Natural Forest Ariquemes	Ariquemes	-10.1	-62.49	Pessenda et al. (1998)
0149	Cerradao Pimenta Bueno	Pimenta Bueno	-11.49	-61.1	Pessenda et al. (1998)
0150	Cerrado Vilhena	Vilhena	-12.42	-66.07	Pessenda et al. (1998)
0151	Tu 1	Pé-de-Pato palm swamp	-16.2	-49.3	Ribeiro et al. (2003)

Table 15. Informations about the records with calibrated age models that were out of the MH time interval defined in this study.

Reference	Site Name	Uncalibrated ^{14}C Age (Years B.P.)	Calibrated ^{14}C Age (Years B.P.)
Behling (1995a)	Lago do Pires	5667 ± 90	384 - 5444
Behling et al. (2001b)	Lago Calado	4640 ± 40	178 - 4178
Behling (2002)	Lagoa da Confusão	14257 ± 126	8 - 51176
Bush et al. (2000)	Lake Geral	6997 ± 106	3815 - 7414
Prieto (1996)	Empalme Querandies	8178 ± 150	1699 - 7857

II.II. References of the tables in the item 3.2. ^{14}C Age Calibration

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Appendix III

III.I. Tables of the item 3.3. American Monsoon System

Table 16. All lakes considered for this study with all the criteria used for the selection of the lakes used.

Chosen for this study	Geographic Location	Calibrated ^{14}C Ages	Multiproxy	Ages (12000 – 1850 years)	References
NO	YES	NO	YES	YES	Guerrero et al. (2000)
NO	YES	NO	YES	NO	Mayle et al. (2000)
NO	YES	NO	YES	NO	Mayle et al. (2000)
NO	YES	NO	YES	YES	Valero-Garcés et al. (2000)
NO	YES	YES	NO	YES	Behling (2001)
NO	YES	NO	YES	YES	Grosjean et al. (2001)
NO	YES	YES	YES	NO	Sifeddine et al. (2001)
NO	YES	NO	YES	YES	García-Rodríguez et al. (2002)
NO	YES	YES	NO	YES	Ledru et al. (2002)
NO	YES	YES	NO	YES	Behling (2003)
NO	YES	YES	YES	NO	Tapia et al. (2003)
NO	YES	NO	YES	YES	García-Rodríguez et al. (2004)
NO	YES	NO	YES	YES	García-Rodríguez et al. (2004)
NO	YES	YES	YES	NO	Jacob et al. (2004)
NO	NO	YES	YES	YES	Moreno et al. (2004)
NO	YES	NO	YES	YES	Piovano et al. (2004)
NO	NO	YES	YES	YES	Gilli et al. (2005)
NO	NO	YES	YES	YES	Haberzettl et al. (2005)
NO	NO	YES	YES	YES	Mayr et al. (2005)
NO	YES	NO	YES	YES	Pessenda et al. (2005)
NO	NO	YES	NO	YES	Irurzun et al. (2006)

NO	YES	YES	YES	NO	Ledru et al. (2006)
NO	YES	YES	YES	NO	Ariztegui et al. (2007)
NO	YES	YES	YES	NO	Fritz et al. (2007)
NO	YES	YES	YES	NO	Moreno et al. (2007)
NO	YES	YES	YES	NO	Sáez et al. (2007)
NO	YES	NO	YES	YES	Urrutia et al. (2007)
NO	NO	YES	YES	YES	Abarzúa and Moreno (2008)
NO	YES	YES	NO	YES	Hodell et al. (2008)
NO	NO	YES	YES	YES	Moy et al. (2008)
NO	YES	YES	YES	NO	Hillyer et al. (2009)
NO	YES	NO	YES	NO	Laprida and Valero Garcés (2009)
NO	YES	YES	YES	NO	Ortega et al. (2010)
NO	YES	YES	YES	NO	Stansell et al. (2010)
NO	YES	YES	YES	NO	Whitney et al. (2011)
NO	YES	YES	YES	NO	Whitney et al. (2011)
NO	YES	NO	NO	YES	Boussafir et al. (2012)
NO	YES	YES	YES	NO	Carvalho do Amaral et al. (2012)
NO	YES	YES	YES	NO	Correa-Metrio et al. (2012)
NO	NO	YES	YES	YES	De Porras et al. (2012)
NO	YES	YES	YES	NO	Escobar et al. (2012)
NO	YES	YES	YES	NO	Reheis et al. (2012)
NO	YES	YES	NO	YES	Zocatelli et al. (2012)
NO	YES	YES	YES	NO	del Puerto et al. (2013)
NO	NO	YES	YES	YES	Elbert et al. (2013)
NO	YES	YES	YES	NO	Kirby et al. (2013)
NO	YES	YES	YES	NO	McGlue et al. (2013)

NO	YES	YES	YES	NO	Niemann et al. (2013)
NO	YES	YES	YES	NO	Stansell et al. (2013)
NO	YES	YES	YES	NO	Yuan et al. (2013)
NO	YES	NO	NO	YES	Gomes et al. (2014)
NO	YES	YES	YES	NO	Metcalfe et al. (2014)
NO	NO	YES	YES	YES	Álvarez et al. (2015)
NO	YES	YES	YES	NO	Blunt et al. (2015)
NO	YES	YES	YES	NO	Guerra et al. (2015)
NO	NO	YES	NO	YES	Reheis et al. (2015)
NO	NO	YES	YES	YES	Shuman et al. (2015)
NO	YES	YES	YES	NO	Grauel et al. (2016)
NO	YES	NO	YES	YES	Horton et al. (2016)
NO	YES	YES	YES	NO	Noble et al. (2016)
NO	YES	NO	NO	YES	Rosenmeier et al. (2016)
NO	YES	YES	YES	NO	Glover et al. (2017)
NO	YES	YES	YES	NO	Spencer et al. (2017)
NO	YES	YES	YES	NO	Spencer et al. (2017)
NO	NO	YES	YES	YES	Fiers et al. (2019)
NO	YES	YES	YES	NO	Guo et al. (2019)
NO	YES	YES	YES	NO	Honke et al. (2019)
NO	YES	YES	NO	YES	Morales et al. (2019)
NO	YES	YES	YES	NO	Speranza et al. (2019)
NO	YES	YES	YES	NO	Cassino et al. (2020)
NO	YES	YES	YES	NO	Hodelka et al. (2020)
NO	YES	YES	YES	NO	Ortega-Guerrero et al. (2020)
NO	NO	YES	YES	YES	Puleo et al. (2020)
YES	YES	YES	YES	YES	Bush et al. (2000)
YES	YES	YES	YES	YES	Behling and Costa (2001)

YES	YES	YES	YES	YES	Jenny et al. (2002)
YES	YES	YES	YES	YES	Turcq et al. (2002)
YES	YES	YES	YES	YES	Turcq et al. (2002)
YES	YES	YES	YES	YES	Turcq et al. (2002)
YES	YES	YES	YES	YES	Turcq et al. (2002)
YES	YES	YES	YES	YES	Turcq et al. (2002)
YES	YES	YES	YES	YES	Irion et al. (2006)
NO	YES	YES	YES	NO	Lupo et al. (2006)
YES	YES	YES	YES	YES	De Toledo and Bush (2007)
YES	YES	YES	YES	YES	De Toledo and Bush (2007)
YES	YES	YES	YES	YES	Bush et al. (2007b)
YES	YES	YES	YES	YES	Bush et al. (2007b)
YES	YES	YES	YES	YES	Bush et al. (2007b)
YES	YES	YES	YES	YES	Enters et al. (2010)
YES	YES	YES	YES	YES	Metcalfe et al. (2010)
YES	YES	YES	YES	YES	Bird et al. (2011)
YES	YES	YES	YES	YES	Smith et al. (2011)
YES	YES	YES	YES	YES	Stutz et al. (2012)
YES	YES	YES	YES	YES	Stutz et al. (2012)
YES	YES	YES	YES	YES	Stutz et al. (2012)
YES	YES	YES	YES	YES	Das et al. (2013)
YES	YES	YES	YES	YES	Das et al. (2013)
YES	YES	YES	YES	YES	Junior et al. (2013)
YES	YES	YES	YES	YES	Stansell et al. (2013)
YES	YES	YES	YES	YES	Stansell et al. (2013)
YES	YES	YES	YES	YES	Aniceto et al. (2014)
YES	YES	YES	YES	YES	Burn et al. (2014)
YES	YES	YES	YES	YES	Cardozo et al. (2014)

YES	YES	YES	YES	YES	Lorente et al. (2014)
YES	YES	YES	YES	YES	Viana et al. (2014)
YES	YES	YES	YES	YES	Carrevedo et al. (2015)
YES	YES	YES	YES	YES	Díaz et al. (2017)
YES	YES	YES	YES	YES	Becker et al. (2018)
YES	YES	YES	YES	YES	Frederick et al. (2018)
YES	YES	YES	YES	YES	Lorente et al. (2018)
YES	YES	YES	YES	YES	Zular et al. (2018)
YES	YES	YES	YES	YES	Jiménez-Moreno et al. (2019)
YES	YES	YES	YES	YES	Utida et al. (2019)
YES	YES	YES	YES	YES	Lyon et al. (2020)
YES	YES	YES	YES	YES	Stansell et al. (2020)

Table 17. Location of the lakes used in this study, with the predominant climate in each of the periods of the Holocene.

Lake	Lat	Long	EH Climate	MH Climate	LH Climate	Reference
Grape Tree Pond	17.89	-76.62			Dry	Burn et al. (2014)
Eastern Lake	30.31	-86.09			Dry	Das et al. (2013)
Laguna de Juanacatlán	20.62	-104.73			Dry	Metcalfe et al. (2010)
Western Lake	30.33	-86.15			Dry	Das et al. (2013)
June Lake	38	-119		Humid	Dry	Lyon et al. (2020)
Lake Kail	16	-91.55		Dry	Humid	Stansell et al. (2020)
Lake Ocotalito	16.95	-91.6	Humid	Dry	Humid	Díaz et al. (2017)
Emerald Lake	39.15	-106.41	Dry	Dry	Humid	Jiménez-Moreno et al. (2019)
Laguna Aculeo	-33.83	-70.9			Humid	Jenny et al. (2002)
Boqueirão Lake	-5.25	-35.54			Humid	Viana et al. (2014), Utida et al. (2019)
Salina da Ponta	-18.98	-56.66			Dry	Becker et al. (2018)
Lonkoy	-37.2	-57.42		Dry	Dry	Stutz et a. (2012)
Lake Tota	5.56	-72.9			Humid	Cardozo et al. (2014)
Lake Marcio	-0.13	-51.08		Dry	Humid	De Toledo and Bush (2007)
Nahuel Rucá	-37.62	-57.43			Dry	Stutz et al. (2012)
Hinojales	-37.57	-57.45		Dry	Dry	Stutz et al. (2012)
Laguna del Maule	-36	-70			Humid	Carrevedo et al. (2015)
Tres Lagunas	-3.05	-79.25		Humid	Dry	Frederick et al. (2018)
Quistococha Lake	-3.83	-73.32		Dry	Humid	Aniceto et al. (2014)
Lago Crispim	-0.59	-47.65		Dry	Humid	Behling and Costa (2001)
Lake Arari	-0.60	-49.14	Dry	Dry	Humid	Smith et al. (2011)
Lake Macuco	-19.04	-39.94		Dry	Humid	Lorente et al. (2014)
Lake Santa Maria	-1.58	-53.60		Dry	Humid	Bush et al. (2007b)
Lagoa do Macuco	-19.04	-39.94		Dry	Humid	Junior et al. (2013)

Lake Tapera	-0.13	-51.2		Dry	Humid	De Toledo and Bush (2007)
Lake Saracuri	-1.68	-53.57		Dry	Humid	Bush et al. (2007b)
Boqueirão Lake	-5.25	-35.54	Humid	Humid	Humid	Zular et al. (2018)
Lake Geral	-1.65	-53.59		Dry	Humid	Bush et al. (2007b)
Laguna Jahuacocha	-10.23	-76.96	Dry	Humid	Humid	Stansell et al. (2013)
Lago Aleixo	-17.99	-42.12		Dry	Humid	Enters et al. (2010)
Laguna Lutacocha	-10.55	-76.72	Dry	Humid	Humid	Stansell et al. (2013)
Caracarana Lake	-3.844	-59.781	Dry	Dry	Humid	Turcq et al. (2002)
Lago Tapajós	-2.79	-55.08	Dry	Dry	Humid	Irion et al. (2006)
Carajás Lake	-19.776	-49.842	Dry	Dry	Humid	Turcq et al. (2002)
Lake Comprida	-1.86	-53.98	Humid	Humid	Humid	Bush et al. (2000)
Dom Helvecio Lake	-19.776	-42.594	Dry	Dry	Humid	Turcq et al. (2002)
Lake Canto Grande	-19.26	-39.94	Humid	Dry	Humid	Lorente et al. (2018)
Feia Lake	-15.572	-47.306	Dry	Dry	Humid	Turcq et al. (2002)
Agua Preta de Baixo Lake	-18.417	-41.846	Dry	Dry	Humid	Turcq et al. (2002)
Laguna Pumacocha	10.7	76.06	Dry	Humid	Humid	Bird et al. (2011)

Table 18. Summer insolation data from the Northern and Southern Hemispheres of the last 12000 years. Data from Berger e Loutre (1991) and available at https://www.ncdc.noaa.gov/paleo-search/study/577.

Year (ka)	15° N Jul (W/m^2)	15° S Jan (W/m^2)
0	440.6	470.35
-1	442.48	468.57
-2	445.62	465.49
-3	449.77	461.39
-4	454.6	456.65
-5	459.67	451.7
-6	464.53	446.98
-7	468.75	442.94
-8	471.92	439.91
-9	473.76	438.17
-10	474.08	437.87
-11	472.84	439.05
-12	470.17	441.6

III.II. References of the tables in the item 3.3. American Monsoon System

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