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LIMNOGEOLOGY IN SOUTHERN SOUTH AMERICA: AN OVERVIEW

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Abstract: One of the major goals of Limnogeology is to provide clues on past Earth system environmental unevenness and feedbacks on longer time scales (100s-1,000s of years) than instrumental records, thus including periods with null or low anthropic influences on the environment. The multiproxy approach in the analysis of lake records allows to gain a wider overview than could be acquired from a single proxy data. Unlike the Northern Hemisphere, reconstructions of Late Pleistocene and Holocene environmental variability across Southern South America have been hampered by the paucity of complete and well-dated paleoclimate archives. However, last decades have been marked by a substantial increase of paleoclimatic research providing new data to analyze past climate variability from a regional perspective in Southern South America.

This special issue include five articles applying a variety of proxy data (physical, chemical and biological) to elucidate climate and environmental changes on various time scales. Contributions cover a wide geographic distribution from the Antarctic Peninsula, Patagonia, Pampean region and NW Argentina up to the Río de la Plata Estuary. Results provide critical elements for further assessments of latitudinal paleo-circulation dynamics and hydroclimatic changes. The recent proliferation of limnogeological studies in Argentina and Uruguay evidence the reinforcement of regional research networks providing comparative and integrative analysis.

Keywords: Limnogeology; multiproxy approach; Antarctica; Patagonian lakes; Pampean lakes; Río de La Plata Estuary.

INTRODUCTION

Paleoclimatologists reconstruct past conditions of Earth's climate system gathering proxy data from "natural archives" such as tree rings, ice cores, lake sediments, peat bogs, ocean sediments, corals, and historical data. Climate archives provide information at different time spans, covering from hundreds to millions of years at a large range of temporal resolutions (Fig. 1).

One major goal in Quaternary paleoclimatology is to reconstruct and understand past Earth system unevenness and feedbacks on longer time scales than the offered by instrumental records, which usually cover the last 100's years. As underlined by the Fifth Assessment Report of the Intergovernmental

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Panel on Climate Change (IPCC; Masson-Delmotte *et al.*, 2013), paleoclimatology provides essential information for understanding present and future climate change. Consequently, is highly necessary to evaluate pre-industrial changes in atmospheric composition, as well as the influence of external solar radiation and volcanic activity to global and regional changes in temperature, cryosphere and hydroclimate conditions.

Lake environments are one of the most sensitive systems in continental settings reacting to extrinsic and intrinsic forcing changes (Cohen, 2003). Lakes and their deposits provide the opportunity to study both present-day and past lake processes at high temporal resolution (Fig. 1). The life of lakes is greatly variable and may range from short-lived ephemeral lakes, like in saline mudflats (e.g., Salinas de Ambargasta; Zanor *et al.*, 2012) to extremely long-lasting lakes, as Lake Tanganyka, which recorded the Earth and ecosystem history over the past 9-12 million years at an annual resolution (Cohen *et al.*, 1997).

Lake research has fascinated scientists since the latter part of the 19th century. Undoubtedly, the contribution of Gilbert (1890), who identified lake paleoshorelines at 300 m above the present-day Great Salt Lake (USA), is a landmark in this field. These deposits were linked to Lake Bonneville, which was the largest late Pleistocene pluvial lake in the North American Great Basin. At the same time, the Swiss naturalist François Forel established the bases for a new discipline named “Limnology” defining it as “the oceanography of lakes” (Forel, 1892). Forel recognized the complexity of lake functioning, considering them as systems in which abiotic and biotic elements are drawn closely together.

Regarding southern South America, one of the first lake studies in the Argentinean Patagonia was done by Caldenius (1932) who provided the first systematic study dealing with glaciations and lakes. He had a visionary approach in the analysis of the past climate system trying to establish, for the first time, the existence of “climate teleconnections” by the comparison of lacustrine varved sediments from Sweden with varved proglacial lake sediments exposed at the terraced walls of the Corintos River in extra-andean Patagonia. After several years, last decades have been marked by a substantial increase of paleoclimatic studies in South America which reinforces the necessity to analyze past climate variability from a regional perspective. The PAGES-sponsored initiative PEP I (Pole Equator Pole through the Americas; Markgraf 2001) represents a milestone using this research strategy gathering for the first time a limited number of available paleolimnogeological records across the Americas (e.g., Ariztegui *et al.*, 2001; Bradbury *et al.*, 2001; Fritz *et al.*, 2001). Since this early effort, a substantial increase in limnogeological studies is shown by the developing of new research programs at middle latitudes in Argentina during the beginning of the 21st century (i.e., Paleo-PAMPAS and Shallow-Lake Programs; see Córdoba *et al.*, this issue and Stutz *et al.*, this issue, respectively) , and the most recent MATES Program (Multiproxy Approach for Tracking Environmental changes in Southern South America), which was designed to integrate paleoclimate research across Argentina and Uruguay.

LIMNOGEOLOGY: BACKGROUND

Limnogeology can be considered as the study and interpretation of physical, geochemical, biological and hydrogeological processes in lakes and in the sedimentary records of lacustrine basins (Last, 2002). When the research is restricted to the Late Pleistocene-Holocene sedimentary record of present-day lake systems, the study is often referred as Paleolimnology.

As defined by Kerry Kelts early in the decade of 1980s, Limnogeology can be ascribed to the study of lake systems, and the advance of this discipline was mainly driven by the progress produced in marine geology within ocean research. Paleoceanography and Limnogeology, in the marine and in the continental setting respectively, employ similar methodologies, techniques and strategies (i.e., multiproxy perspective) to explore the records of past environmental and climate variability. Among these methodologies sediment coring is the most common technique for obtaining data both in Paleoceanography and Limnogeology research.

Limnogeology is an interdisciplinary subject by nature, and involves methods and tools normally used in a wide range of disciplines such as agronomy and soil science, botany, climatology, chemistry and geochemistry, ecology, engineering, geography, geology, hydrology, physics and geophysics, and zoology (e.g., Kelts, 1987; Last, 1999; Last and Smol, 2001a; Cohen, 2003; Last and Ginn, 2005;

Birks and Birks, 2006; Ariztegui *et al.*, 2008, Zolitschka *et al.*, 2013). An excellent update and overview on methodological developments used in paleolimnology is provided in "Advances in Paleolimnology" published by PAGES (http://www.pages-igbp.org/products/pages-magazine/961-17-3-advances-in-paleolimnology; Pienitz *et al.*, 2009).

Since the 1970's there was a growing interest in lacustrine geological processes and lake deposits covering a wide range of topics from basin evolution, sedimentology, geochemistry, mineralogy, paleoecology and climatic evolution (e.g., Eugster and Hardie, 1978; Kelts and Hsü, 1978; Kelts, 1987; Katz, 1990; Anadón *et al.*, 1991; Fritz *et al.*, 1991; Gierlowski-Kordesch and Kelts, 2000; Smith *et al.*, 2008; Renaut and Gierlowski-Kordesch, 2010). The marked expansion of limnogeology within Earth sciences can be attributed to: (i) the potential of lake sediments as source of industrial minerals and fossil fuels (Kelts, 1988; Last and Ginn, 2005), (ii) Quaternary paleoclimate studies (Zolitschka *et al.*, 2013), (iii) water resources management (Davidson and Jeppesen, 2013), and (iv) environmental studies (Smol, 2009).

The multiproxy approach in Limnogeology

Lake sediments include terrigenous, chemical and biogenic sediments, as well as cosmogenic and volcanogenic particles, fossils and pollutants (Cohen, 2003). Therefore, lacustrine sedimentary records can store a temporally-integrated signal of natural and anthropic processes through the deposition of biotic and abiotic materials derived from the lake itself, the land beyond the catchment area, and the atmosphere. The archive (sedimentary record) is the medium in which the response of a sensor (lake system) to environmental forcing (hydrological changes) is recorded. In other words, the sensor acts in response to the environment and leaves an imprint in the archive (Evans *et al.*, 2013). *Proxy data* (e.g., mineralogy, geochemistry of sediments, isotope composition, biomarkers, diatom assemblages, among the most widely used) are obtained by analytical techniques to further reconstruct past conditions (Last and Smol, 2001b). The word has the same root as *approximation* and is used as surrogates for other variables, such as climate. Equally, *proxy records* (e.g., tree-rings; lake sediments; corals, glacier, among others; Fig. 1) are the "archives or recorders" that accumulate and retain information from past environmental conditions. Because of the complex network of interactions throughout the ecosystems, it is desirable to analyze as many proxies as possible, in order to gain a wider overview of the situation than could be acquired from a single proxy data (Smol, 2009). Such an investigation is called a multiproxy study.

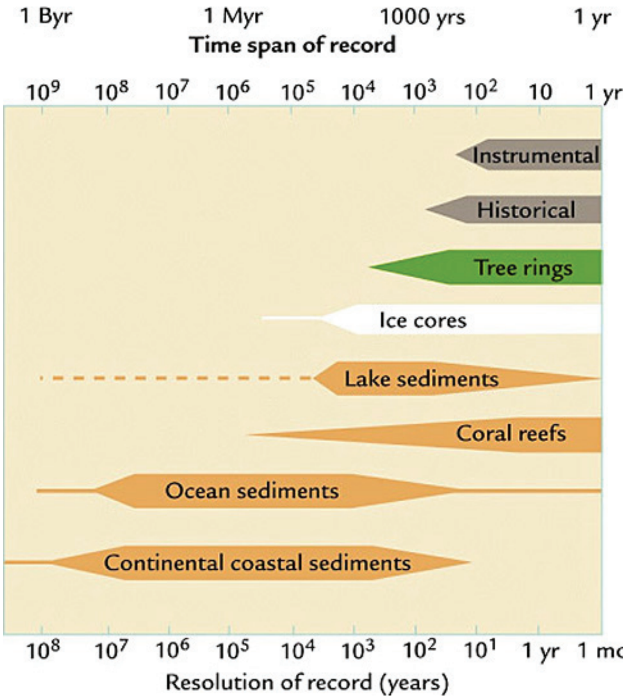

Figure 1. Time span and temporal resolution of continental and marine climate archives. Long-term archives are comparatively poorly resolved in time when compared to short-term and thus higher resolved records (National Oceanic and Atmospheric Administration Paleoclimatology Program; https://www.ncdc.noaa.gov/data-access/paleoclimatology-data).

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The South American continent contains a diverse array of documentary and natural climate archives such as glaciers and ice caps, tree rings and lake sediments that can be used to better understand climate changes and atmosphere dynamics during the last few centuries (Villalba *et al.*, 2009).

Particularly, the development of Limnogeology in Southern South America was first focused in Patagonia since at that latitudes, lake archives allow to perform high resolution studies of the

Last Glacial-to-interglacial transition and Holocene (Stine and Stine, 1990; Ariztegui *et al.*, 1997, 2008; Markgraf, 1998; Gilli *et al.*, 2005; Kilian and Lamy, 2012; Recasens *et al.*, 2012; Massaferro *et al.*, 2013; Zolitschka *et al.*, 2013). The substantial increase of paloclimatic studies in southernmost Argentina showed the necessity to analyze the past climate variability from a more regional perspective promoting the expansion of lake research across the subtropical plains (e.g., Piovano *et al.*, 2009; García Rodriguez *et al.*, 2009; Tonello and Pietro, 2010; Stutz *et al.*, 2010, 2012; del Puerto *et al.*, 2013; Laprida *et al.*, 2014; Guerra *et al.*, 2015; Córdoba *et al.*, this issue; Stutz *et al.*, this issue), as well as in North Western Argentina (e.g. Valero Garcés *et al.*, 2000; Lupo *et al.*, 2006a,b; Tchilinguirián *et al.*, 2013). Studied lakes in southern South America and a detailed list of references is presented in figure 2.

Results from all across southern South America (Fig. 2) provide critical elements for comparing latitudinal paleo-circulation dynamics and hydro-climatic response during the Late Pleistocene and throughout the Holocene (Ariztegui *et al.*, 2001 ; Piovano et al., 2009)). Paleolimnological reconstructions show that a downscaling approach is better than the former "smoothed" sub-hemispheric-scale reconstructions obtained by using a reduced set of paleoenvironmental data. In addition, ongoing research based on multiple climate archives pinpoint that additional high-quality proxy records are still needed to resolve the finer temporal and spatial structure of past climate variations across southern South America (see Villalba *et al.*, 2009).

Pampean lakes as sentinels of hydroclimate changes

Although lakes make up a small percentage of the Earth's surface, they act as sentinels by providing signals that reflect the influence of climate change in their much broader catchments (Williamson *et al.*, 2009; Adrian *et al.*, 2009). For instance, the well-known hydrological change occurred in central Argentina during the 1970s, triggered pervasive and abrupt lake water-level rises across the subtropical Pampean plains (Piovano *et al.*, 2002; Pasquini *et al.*, 2006; Troin *et al.*, 2010; Córdoba, 2012; Guerra *et al.*, 2015; Córdoba *et al.*, this issue). The change in the regional hydrological balance is ruled by the South American Monsoon System activity (Jacques-Coper and Garreaud, 2014) and it has been recognized as one of the largest rainfall increase occurred in continental environments (Giorgi, 2002). Thus, the conspicuous hydrological shift occurred after the 1970s emphases the importance of pampean paleolimnological archives to analyze past hydrological variability at a longer time-scale than the provided by historical and instrumental records.

The regional hydrological balance fluctuation throughout the Pampean plains triggered changes in lake water levels, the chemistry and biology of the water column and a variety of sedimentary processes that were further recorded in the lake sediments. Therefore the type of sedimentary facies, endogenic and authigenic minerals, geochemical composition of sediments, stable isotope signature of organic matter, biomarkers, biological remains, among other proxies, become useful data to reconstruct past hydroclimate conditions (e.g., Piovano *et al.*, 2002; Piovano *et al.*, 2004; Stutz *et al.*, 2010, 2012; Córdoba, 2012; Laprida *et al.*, 2014; Coianiz *et al.*, 2015; Guerra *et al.*, 2015; among others).

For example, Laguna Mar Chiquita (30°54'S – 62°51'W; central Argentina), the largest closed-saline lake in South America, has clearly responded to the 20th century hydrologic changes through abrupt lake water level fluctuations (Fig. 3a). Using a well-constrained ^{210}Pb chronology, Piovano *et al.* (2002) identified the sedimentological response of the lake system to the last 100 years of documented extreme lake water-level changes (Fig. 3b and c). Proxy data (Fig. 3d) were first calibrated with the instrumental record of water levels and salinities. The comparison of hydroclimatic conditions to sedimentological and geochemical features, isotope compositions, diatom assemblages, pigments and biomarkers shows a consistent pattern, which allows to formulate a well constrained multiproxy-based evolutionary model for the lake at different water-level conditions (high, intermediate and low lake stages; Fig. 3). Subsequently, the extrapolation of the multiproxy-based model over longer-term sedimentary records – dated by ^{14}C technique – allowed the reconstruction of hydrological changes for the subtropical plains of Argentina since the Last Glacial Maximum to the present (Piovano *et al.*, 2009).

Ongoing research across the Pampean plains (Córdoba, 2012, this issue; Guerra *et al.*, 2015; Stutz *et al.*, this issue) provides insights into environmental variability at a longer timescale than the

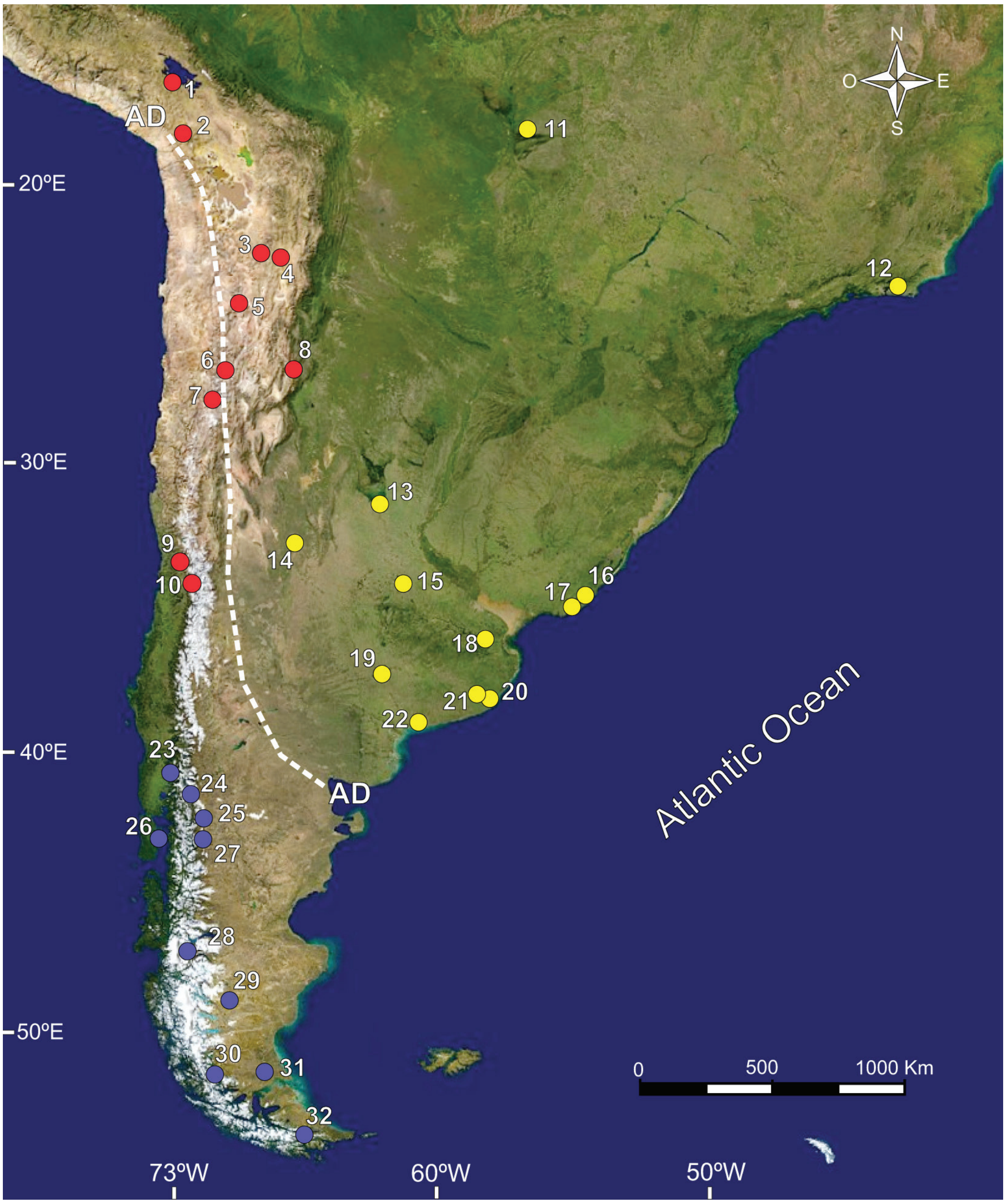

Figure 2. Limnogeological records in Southern South America. Dashed-line indicates the position of the South America Arid Diagonal (AD). The numbers refer to the location of the published limnogeological records covering the Central Andes (red circles), Andean and Extra Andean Patagonia (blue circles) and southeastern South American (yellow circles). (1) Lago Titicaca (Abbott *et al.*, 1997; Fritz *et al.*, 2007); (2) Lago Chungará (Sáez *et al.*, 2007); (3) Laguna Pululos (Lupo *et al.*, 2006b); (4) Laguna Pozuelos (McGlue *et al.*, 2012, 2013); (5) Laguna Miscanti (Grosjean *et al.*, 2001); (6) Laguna El Peinado (Valero-Garcés *et al.*, 2000); (7) Laguna del Negro Francisco (Grosjean *et al.*, 1997); (8) Lagunas de Yala (Lupo *et al.*, 2006a); (9) Laguna Aculeo (Jenny *et al.*, 2003); (10) Laguna del Maule (Carrevedo *et al.*, 2015); (11) Laguna La Gaiba (Metcalfe *et al.*, 2014); (12) Cabo Frio lagoonal system (Sylvestre *et al.*, 2005); (13) Laguna Mar Chiquita (Piovano *et al.*, 2002, 2004); (14) Salina del Bebedero (González and Maidana, 1998, García, 1999); (15) Laguna Melincué (Guerra *et al.*, 2015); (16) Rocha Lagoon (García-Rodríguez *et al.*, 2004); (17) Laguna Blanca (García-Rodríguez *et al.*, 2002; del Puerto *et al.*, 2006); (18) Laguna Chascomús (Laprida and Valero-Garcés, 2009); (19) Lagunas Encadenadas del Oeste (Córdoba, 2012; Córdoba *et al.*, this issue); (20) Laguna La Brava (Irurzun *et al.*, 2014); (21) Lagunas Lonkoy, Nahuel Rucá, Hinojales and Mar Chiquita (Stutz *et al.*, 2012, this issue); (22) Laguna del Sauce Grande (Fontana, 2005); (23) Lago Puyehue (Bertrand *et al.*, 2005; Chaprón *et al.*, 2006); (24) Lago Mascardi (Ariztegui *et al.*, 1997); (25) Lago Frías (Ariztegui *et al.*, 2007); (26) Lago Melli (Abarzúa and Moreno, 2008); (27) Lago El Trébol (Massaferro *et al.*, 1999; Irurzun *et al.*, 2006); (28) Lago Cisnes (Álvarez *et al.*, 2015); (29) Lago Cardiel (Stine and Stine,1990; Gilli *et al.*, 2005); (30) Lago Guanaco (Moreno, 2004; Moy *et al.*, 2008); (31) Laguna Azul and Laguna Potrok Aike (Haberzettl *et al.*, 2005; Mayr 2005); (32) Lago Fagnano (Waldmann *et al.*, 2010).

perceived by the inhabitants and historical records. This basic knowledge can be used to help leaving behind the idea of "steady climate" and thus, it also provides tools to efficiently carry out an integrated management of water resources with evident major societal impact.

The validity of assumptions and the uncertainty on the reconstructions must be carefully considered. Many challenges remain. Proxy data are *estimates* rather than *measurements* of the environmental variables of interest. The multiple proxy sources (e.g., tree rings, speleothems, lake records, etc.) are a natural filter which invariably imposes statistical distortion on the reconstructed variable. Better understanding and quantification of this distortion is needed, especially if reconstructions are to gain widespread use by governmental and private agencies and other entities in water resources management and planning (Meko and Piovano, 2015). This philosophy of research is likely to rely increasingly on a multiproxy approach, and the proliferation of regional studies will provide fertile ground for comparative and integrative analysis.

THIS SPECIAL ISSUE IN SHORT

This special issue *"Limnogeology in Southern South America: Tracking environmental variability from the Late Glacial to the 21st Century"* compiles a set of selected papers presented at the symposium "*Paleolimnology: Environmental reconstructions from the Late Glacial to the Anthropocene*" held during the XIX Congreso Geológico Argentino in Córdoba (Argentina) in 2014. The aim of this issue is to present the state of the art of ongoing limnogeological and estuarine research in southern South America. The five articles in this issue use a variety of proxy data to elucidate climate and environmental changes on various scale of time ranging from the Last Glacial Maximum and Holocene (including the Little Ice Age) to the most recent variability during the 20th and 21st centuries. The geographic distribution of studied sites is wide, and includes the Antarctic Peninsula, Patagonia, Pampean region and NW Argentina, as well as the Río de la Plata Estuary.

The use of proxy data is addressed in two papers. Chaparro *et al*. evaluate magnetic proxies in lake sediments from James Ross Archipelago (NE Antarctic Peninsula). The evident relationships between magnetic concentration and magnetic grain size with physicochemical variables of lakes could be ruled by the lake catchment-type, environmental conditions, diagenetic process, among other controls. The authors conclude that magnetic proxies, besides being useful environmental indicators, can be additionally used for correlating lake sediments. Laprida *et al*. summarize the current knowledge on paleolimnological research at different latitudes in Argentina (Patagonia, Pampean and North Western regions) using biological proxies, particularly ostracods (Crustacea) and chironomids (Diptera). The contribution reveals that these bio-proxies permitted recognize long- and mid-term climate and environmental trends and high-frequency climatic events of global interest, such as the Younger Dryas, the Antarctic Cold Reversal, the "4.2 ka Dry Event", and the Little Ice Age, as well as climate changes occurred during the 20th century, including anthropogenic impact.

Paleoenvironmental and paleoclimatic reconstructions of shallow Pampean lakes are addressed in two papers, illustrating that the combination of multiproxy and multi-site approaches in limnogeological analyses is critical to define regional patterns of past variability. Stutz *et al*. summarize paleolimnological research throughout the South Eastern Pampean plains of Argentina in order to reconstruct shallow-lakes evolutionary history and regional environmental reconstructions, with the ultimate goal of inferring past climatic conditions. The multiproxy analysis is based on diverse biological indicators like pollen, non-pollen palynomorphs, plant macrofossil remains and associated fauna. These records, spanning a time since the middle Holocene, document a consistent evolutionary pattern in the region. Brackish-shallow lakes with clear water phases were dominant during the middle Holocene up to ca. 2,000 cal a BP when a gradual change to more turbid conditions occurred, reaching a maximum by 700-500 cal a BP. The synchronous change to a turbid face in all studied sites suggests a regional climatic forcing like an increase in precipitation. This contribution stresses the importance of understanding the dynamics and functioning of shallow lakes for developing more reliable paleoenvironmental and paleoclimatic reconstructions. In turn, Córdoba *et al*. review paleolimnological and instrumental data along a transect from 30°S to 37°S to define hydroclimate changes from the Little Ice to the

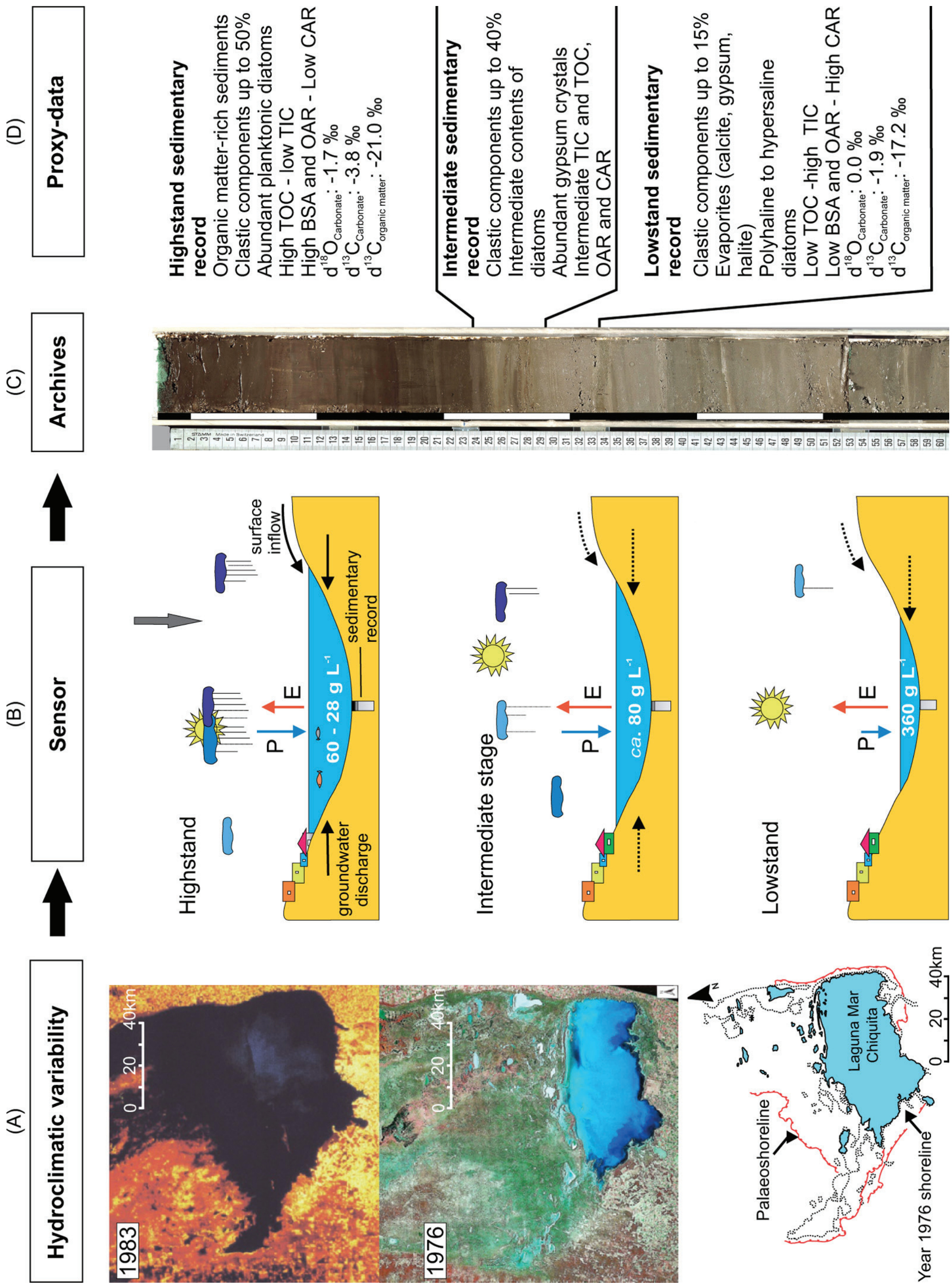

Figure 3. Multi-proxy model showing the relationships between forcings (hydroclimate variability), sensor (lake), archives (sedimentary records) and proxy data (modified from Piovano *et al.*, 2009). a) Satellite images showing Laguna Mar Chiquita hydrological surface variations between years 1976 and 1983 (images from http://conae.gov.ar). The scheme on the bottom left shows the extension of the lake (in blue) and paleoshorelines mapped from satellite image corresponding to year 1976. b) Laguna Mar Chiquita hydrological conceptual model for changing lake stages. P-E arrows represent the precipitation (P) evaporation (E) balance; the relative length of the arrows indicates the predominance of either P or E. Higher river runoff and groundwater inputs are indicated by solid arrows, whereas dotted arrows display comparatively low inputs. Lake water salinity is displayed in g L^{-1}. c) Sedimentary record of lake variability. Note the uppermost organic-rich sediments (darker colours) accumulated after the hydrological shift occurred during the 70´s. d) Main sedimentological, geochemical and mineralogical proxy data corresponding to high, intermediate and low lake stands. Proxy data were measured on a ^{210}Pb dated sedimentary record and further calibrated to the available instrumental record of water lake levels and salinities (indicated in the conceptual model). TOC: total organic carbon, TIC: total inorganic carbon, BSA: bulk sediment accumulation rate, OAR: organic accumulation rate, CAR: carbonate accumulation rate, REE: rare earth elements. Isotope ratios are average values.

20th-21st century. The analysis of instrumental data blended with multiproxy studies (sedimentology, geochemistry, isotope composition) on ^{210}Pb-dated sedimentary cores provide the framework for building a sedimentary model of shallow closed-lakes with highly variable water depth and salinity. The reconstruction of high-frequency (decadal) and low-frequency (>10^2 years) hydroclimatic variability becomes relevant to evaluate the well-known "hydroclimatic jump" occurred in south eastern South America after the mid-1970's. Results show that Pampean lakes are good sensors of high- and low-frequency changes in the recent and past hydrological balance and, therefore, they provide excellent records for deciphering past atmospheric circulation changes at subtropical latitudes in South America.

The link between the hydrological variability of Río de La Plata drainage Basin and the corresponding sediment fluxes in the fluvio-marine setting is addressed by Marrero and co-authors. Chemical proxy data (elemental ratios, e.g., Ca/Ti) from ^{210}Pb dated sediment cores retrieved in the estuarine setting were inspected to infer the dominance of continental or marine sources on fluvio-marine sediments during the past 100 yr. In addition, the link between climatic indices (PDO, SOI, AMO) and the last century fluvial discharges of both Paraná and Uruguay Rivers were evaluated. These data show that the dominance of positive discharges anomalies, after the decade of 1970 is mirrored by higher accumulation rate of terrigenous sediments, and grain sizes, as well as low Ca/Ti ratio pointing toward a dominant continental source of sediments. Conversely, comparatively lower sedimentation rates and finer grain size are recorded in sediments accumulated prior 1970s, matching negative anomalies discharges. This study shows that sediments from the inner-shelf of Uruguay provide a unique archive to disentangle past continental runoff variability and thus precipitation changes over south eastern South America.

This special issue can, of course, only sample the vast and continually expanding research in Limnogeology by Argentinean and Uruguayan researchers. Limnogeology is likely to rely increasingly on a multiproxy approach, and the proliferation of multi-site studies will provide fertile ground for comparative and integrative analysis. Or, as Nanna Noe-Nygaard stated back in 1998 *"Unravelling the history of a lake basin is like solving a criminal case where all possible methods must be applied to solve the mystery"*.

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