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Climatic and lacustrine morphometric controls of diatom paleoproductivity in a tropical Andean lake

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A B S T R A C T

The coupling of lake dynamics with catchment biogeochemistry is considered the key element controlling primary production in mountain lakes at time scales of a few decades to millennia, yet little is known on the impacts of the morphometry of lakes throughout their ontogeny. As Lake Chungará (Central Andean Altiplano, northern Chile) experienced long-term lake-level fluctuations that strongly modified its area:volume ratio, it is an ideal system for exploring the relative roles that long-term climatic shifts and lake morphometry play on biosiliceous lacustrine productivity. In this paper, we review previous data on the percent contents of total organic carbon, total inorganic carbon, total nitrogen, total biogenic silica, isotopic composition of organic matter, carbonates, and diatom frustules, as well as data on the abundance of the chlorophycean *Botryococcus braunii* in this lake for the period 12,400–1300 cal yr BP. We also include new data on organic carbon and biogenic silica mass accumulation rates and the diatom assemblage composition of an offshore core dated using ^{14}C and U/Th.

Biosiliceous productivity in Lake Chungará was influenced by shifts in allochthonous nutrient inputs related to variability in precipitation. Humid phases dated at approx. 12,400 to 10,000 and 9600 to 7400 cal yr BP coincide with periods of elevated productivity, whereas decreases in productivity were recorded during arid phases dated at approx. 10,000 to 9600 and 7400 to 3550 cal yr BP (Andean mid-Holocene Aridity Period). However, morphometry-related in–lake controls led to a lack of a linear response of productivity to precipitation variability. During the late Glacial to early Holocene, lowstands facilitated complete water column mixing, prompting episodic massive blooms of a large centric diatom, *Cyclostephanos* cf. *andinus*. Thus, moderate productivity could be maintained, regardless of aridity, by this phenomenon of morphometric eutrophy during the early history of the lake. The subsequent net increase in lake level introduced modifications in the area of the epilimnion sediments versus the total volume of the epilimnion, preventing complete overturn. Surpassing a certain depth threshold at approx. 8300 cal yr BP caused cessation of the morphometric eutrophy conditions associated with *Cyclostephanos* cf. *andinus* superblooms. After 7300 cal yr BP, the lake experienced a decrease in biosiliceous productivity and a change of state that involved a stronger dependence on precipitation variability, with a lesser contribution of diatoms to the total primary productivity. Our results show that the interpretation of lacustrine paleoproductivity records as paleoclimatic archives needs to take into account the effects of changes in the epilimnion sediment area to epilimnion volume ratio in association with lake ontogeny.

1. Introduction

Photosynthetic activity in periodically stratified lakes is generally restricted by phosphorous and nitrogen concentrations in the

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epilimnion because the waters underneath, although richer in these limiting nutrients, do not receive sufficient light to sustain significant primary productivity (Sterner, 2008). This vertical segregation is usually eliminated when deep mixing of the water column transports bottom nutrient-rich waters upward to the euphotic zone. Nutrient and mixing gradients are, therefore, primary drivers of phytoplankton dynamics and productivity in aquatic ecosystems (Winder and Hunter, 2008). The morphometric characteristics of the lake basin influence the total epilimnion volume and the degree of water column mixing and, thus, can be an important influence on lake productivity (Imboden and Wüest, 1995; Wetzel, 2001).

The relative role that lake morphology plays in affecting productivity likely varies geographically and over time. In a classical paper, Rawson (1955) reviewed data from a series of large lakes and concluded that lake morphometry is a determinant factor in lacustrine productivity; this result, however, could not be reproduced by Brylinsky and Mann (1973), who considered morphometry as having relatively little impact on phytoplankton production. These ecological studies relied on space-for-time substitution approaches (Smol, 2008) and did not consider changes in productivity that could be associated with modifications in the morphology of an individual lake over long periods of time. Moreover, despite evidence generated by Quaternary paleoecologists (Engstrom et al., 2000), many limnologists still assume a traditional model of progressive lake eutrophication over time (Deevey, 1955). Indeed, temporal change in phytoplankton communities and their function is a time scale-dependent process, the study of which has largely ignored the long-term variability resulting from lake ontogeny (Anderson, 1995). Data analyses on broad time scales provide new insight into the role that both climate and local physiographic factors have in affecting the productivity of lake systems, and disentangling the relative importance of these two factors is required in Quaternary paleoclimatic reconstructions that rely in part on the study of changes in paleoproductivity inferred from biosiliceous proxy data (e.g., Johnson et al., 2004; Mackay, 2007; Castañeda et al., 2009).

Lakes in the Central Andean Altiplano experienced strong lake-level fluctuations during the Late Quaternary that altered their surface area:volume ratios (Placzek et al., 2009). This variation makes these lakes ideal systems for exploring not only the effects of long-term climatic shifts on primary productivity but also the way in which the lake morphometry dictates how lake-level fluctuations influence productivity. The millennial-scale moisture balance of the Atlantic-Amazon-hydrologic system is strongly influenced by precessional changes in solar insolation (e.g., Rowe et al., 2002) and tropical Atlantic sea-surface temperature (SST) variation (Baker et al., 2001). Changes in the Equatorial Pacific SST and El Niño-Southern oscillation (ENSO) variability may also have played a role (Polissar et al., 2013). All of these factors contributed to changes in lake levels that, in turn, affected the composition of planktonic communities (e.g., Tapia et al., 2003). Regardless, very little is known about the effects of long-term lake-level variability on the functional properties, such as lacustrine productivity, of regional limnological systems.

Lake Chungará (Central Andean Altiplano, northern Chile) is a surficially closed lake that has undergone significant changes in water level during the last 12,400 years (Sáez et al., 2007). Due to its complex bottom topography, these changes produced important modifications in the surface:volume ratio during its ontogeny, making it a good system to test the relative importance that climate and lake morphometric characteristics have on primary productivity variation. There is appreciable knowledge based on multiproxy evidence of the major changes that occurred in the lake since the Late Glacial, including sedimentary facies characterization (Sáez et al., 2007) and the isotopic composition of bulk organic matter ($\delta^{13}C_{org}$, $\delta^{15}N_{org}$; Pueyo et al., 2011), carbonates ($\delta^{18}O_{carbonate}$, $\delta^{13}C_{carbonate}$; Pueyo et al., 2011), and diatom frustules ($\delta^{18}O_{diat}$, $\delta^{13}C_{diat}$; Hernández et al., 2008, 2010, 2011, 2013). A moisture balance reconstruction based on magnetic susceptibility, X-ray fluorescence (XRF), X-ray diffraction (XRD), total carbon and total organic carbon (TC and TOC), biogenic silica (BSi) and a grey–color curve of the sediment data (Giralt et al., 2008) has also been published. Despite the large number of proxies analyzed, an overall picture of the causes underlying paleoproductivity changes in the lake is still lacking.

In this paper, we integrate previous and new (diatom assemblage composition, organic carbon and biogenic silica mass accumulation rates) multiproxy data on the paleoenvironmental evolution of Lake Chungará to develop an evolutionary model of long-term productivity trajectories in a high-elevation tropical lake. We also study the relationship between changes in productivity and the main climatic events recorded in the Central Andean Altiplano as well as the potential role that lake morphometry could have played. We show how the imprinting of primary climatic forcing signals in the sedimentary record is decisively modulated by the effects of changes in the ratio of the area of the epilimnion sediments with respect to the total volume of the epilimnion throughout the ontogeny of the lake.

2. Study site

2.1. Physiographic and limnological features

Lake Chungará (18°15′ S, 69°09′ W, 4520 m a.s.l., Fig. 1) was formed in the Paleo-Lauca River valley between 15,000 and 17,000 yr BP after the partial collapse of the Parinacota volcano, which originated at its earliest stages a very permeable barrier of breccia deposits dominated by large block-size particles (Clavero et al., 2002; Hora et al., 2007). The lake has a maximum length of 8.75 km, a maximum water depth of 40 m, a surface area of 21.5 km^2, and a volume of 400×10^6 m^3 (Mühlhauser et al., 1995; Herrera et al., 2006). The western and northern lake margins are steep, whereas the eastern and southern margins are gentle, forming extensive shallow (less than 7 m deep) platforms (Fig. 1B). The main inlet to the lake is the small Chungará stream (300–460 l s^{-1}), and the main route of water loss is via evaporation (3.10^7 m^3 yr^{-1}). Groundwater outflow to the nearby Cotacotani lakes has been estimated as approximately 6–7 x 10^6 m^3 yr^{-1} (Risacher et al., 1999; Dorador et al., 2003).

Lake Chungará is a cold-polymictic and moderately saline lake, which thermally stratifies from January to April (Mühlhauser et al., 1995). It contains 1.2 g l^{-1} of total dissolved salts, with a conductivity ranging between 1500 and 3000 μS cm^{-1}, and a water chemistry of the $Na–Mg–HCO_3–SO_4$ type (Mühlhauser et al., 1995; Dorador et al., 2003). The lake has been classified as oligo-mesotrophic or meso-eutrophic according to its chlorophyll-*a* concentration and photosynthetic activity, respectively (Mühlhauser et al., 1995). Most of the primary productivity is performed by diatoms, but cyanobacteria and chlorophyceans also contribute importantly during spring and summer (Dorador et al., 2003; Márquez-García et al., 2009). Large concentrations of phosphorous were recorded (Mühlhauser et al., 1995), but the lake is limited by nitrogen (Dorador et al., 2003; Márquez-García et al., 2009). Maximum chlorophyll-*a* concentrations have been recorded during autumn (Dorador et al., 2003).

The lake receives precipitation from the Atlantic Ocean. Annual rainfall in the Chungará region is approximately 350 mm yr^{-1} but does vary (100–750 mm yr^{-1}). The mean temperature is 4.2 °C. Humidity in the region is advected from the