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Geomicrobiological investigations in subsaline maar lake sediments over the last 1500 years

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ABSTRACT

Living microorganisms inhabit every environment of the biosphere but only in the last decades their importance governing biochemical cycles in deep sediments has been widely recognized. Most investigations have been accomplished in the marine realm whereas there is a clear paucity of comparable studies in lacustrine sediments. One of the main challenges is to define geomicrobiological proxies that can be used to identify different microbial signals in the sediments. Laguna Potrok Aike, a maar lake located in Southeastern Patagonia, has an annually not stratifying cold water column with temperatures ranging between 4 and 10 °C, and most probably an anoxic water/sediment interface. These unusual features make it a peculiar and interesting site for geomicrobiological studies. Living microbial activity within the sediments was inspected by the first time in a sedimentary core retrieved during an ICDP-sponsored drilling operation. The main goals to study this cold subsaline environment were to characterize the living microbial consortium; to detect early diagenetic signals triggered by active microbes; and to investigate plausible links between climate and microbial populations. Results from a meter long gravity core suggest that microbial activity in lacustrine sediments can be sustained deeper than previously thought due to their adaptation to both changing temperature and oxygen availability. A multi-proxy study of the same core allowed defining past water column conditions and further microbial reworking of the organic fraction within the sediments. Methane content shows a gradual increase with depth as a result of the fermentation of methylated substrates, first methanogenic pathway to take place in the shallow subsurface of freshwater and subsaline environments. Statistical analyses of DGGE microbial diversity profiles indicate four clusters for Bacteria reflecting layered communities linked to the oxidant type whereas three clusters characterize Archaea communities that can be linked to both denitrifiers and methanogens. Independent sedimentary and biological proxies suggest that organic matter production and/or preservation have been lower during the Medieval Climate Anomaly (MCA) coinciding with a low microbial colonization of the sediments. Conversely, a reversed trend with higher organic matter content and substantial microbial activity characterizes the sediments deposited during the Little Ice Age (LIA). Thus, the initial sediments deposited during distinctive time intervals under contrasting environmental conditions have to be taken into account to understand their impact on the development of microbial communities throughout the sediments and their further imprint on early diagenetic signals.

1. Introduction

Microbial activity in both water column and most recent sediments is one of the dominant factors ruling organic matter reworking (Meyers and Ishiwatari, 1993). Carbon consumption by microbes in the sediments takes place during early diagenesis resulting in the transformation of the organic fraction through successive steps (Nealson, 1997). As the potential of metabolic reactions (i.e. ΔGibbs free energy) tends to decrease with the depletion of available oxidants and through the organic matter degradation chain (Konhauser, 2007), microbial communities respond to substrates differentiation and further adapt through depth (Boschker and Middelburg, 2002) by forming layered-type communities (Nealson and Stahl, 1997). Organic matter diminution, C/N ratio changes and even stable carbon isotopic fractionation (Lehmann et al., 2002) are often post-depositional effects. They can be attributed to the influence of sedimentary microbial

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colonies via their nutrient consumption and associated mineralization and remineralization processes (Meyers, 1997; Arrigo, 2005). Denitrification and/or methanogenesis are depth-related examples of such non-steady state processes generating substrate modifications (Freudenthal et al., 2001).

The evolution of anaerobic respiration types and nutrient availability throughout depth in an aquatic system would imply a quick and gradual diminution of microbial activity in the sediments with methanogenesis as the final degradation process. Additionally, other parameters often related to initial depositional conditions have remarkable effects on the structure of microbial communities. Time intervals of variable environmental conditions can be reflected in the lacustrine sedimentary record as changes in sedimentation rate, trophic level and productivity. However, several physicochemical features related to these changes such as OM content, oxygen penetration and pH have a non-uniform preservation which can be affected by post depositional microbial activity (Meyers and Lallier-Vergès, 1999; Zeng et al., 2009). Hence, quantification and characterization of microbial communities are necessary when using organic matter proxies for paleoenvironmental reconstructions. Analogously, constraining microbial influence in lacustrine sediments requires paleoclimatic studies to identify organic substrates in which microbes preferentially settled. The latter is highly dependent of the different sources of OM (i.e. allochthonous or autochthonous sources such as vegetation from the catchment and/or water column production, respectively).

Initial sampling conditions are fundamental in geomicrobiological investigations in order to avoid potential sources of contamination. In this study a specially tailored field sampling methodology was first applied to recover sediments under as much sterile conditions as possible (Vuillemin et al., 2010). A multi-proxy methodological approach including grain size, water content, loss on ignition, elemental analyses and calcimetry was used to infer primary sources as well as consumption of specific fractions of the organic matter. These results were further compared to geomicrobiological datasets that included *in situ* ATP (adenosine 5′-triphosphate) measurements, DAPI cell counts, DGGE gel patterns analyses, and methane content obtained via the headspace technique. ATP is a molecule only produced by living organisms and is used to assess microbial activity (Bird et al., 2001). DAPI (4′,6′-diamidino-2-phénylindole) is a fluorochrom that binds to DNA allowing to count microbial cells under fluorescence microscopy and further quantify them (Haglund et al., 2003). DGGE, a 16S rRNA fingerprinting technique, indicates microbial diversity and richness (Muyzer and Smalla, 1998; Schäfer and Muyzer, 2001).

The dataset presented in this contribution has been produced from a 1 m long gravity core retrieved in 2008. The comparison of these data with a previous study of the Laguna Potrok Aike climatic record covering the last 1500 years (Haberzettl et al., 2005) allowed us to establish a link between the behavior of microbial communities and climate.

2. Site location

Laguna Potrok Aike (52°S) is a maar lake located in the Pali Aike volcanic field in southern Patagonia, Argentina (Zolitschka et al., 2006). The lake is under the influence of confluent air masses making this presently perennial system a crucial site for the reconstruction of former fluctuations of the westerlies as well as the waxing and waning of the Patagonian ice caps (Hulton et al., 2002; Haberzettl et al., 2007a; Mayr et al., 2007a). It has already been the focus of many investigations dealing with its geometry and stratigraphy (Anselmetti et al., 2008; Gebhardt et al., 2011) as well as its record of changing organic sources and microfossil assemblages (Wille et al., 2007; Mayr et al., 2009; Recasens et al., in press).

Table 1
Mean surface water values of pH, temperature, salinity, and nitrates, sulfates, iron and manganese concentrations (from Zolitschka et al., 2006; Mayr et al. 2007b). Ion concentrations are determinant for microbial anaerobic respiration pathways.

$T°$	pH	Salinity	NO_3^-	SO_4^{2-}	Fe	Mn
4–12 (°C)	8.8	2.31 (g/L)	46.15 (μM)	279.86 (μM)	0.29 (μM)	0.04 (μM)

A multi-proxy record based on five different cores retrieved through the PASADO project has established lake level fluctuations and provides a paleoclimatic reconstruction for the Late Pleistocene and the Holocene (Haberzettl et al., 2007b). Table 1 summarizes several water column parameters that have been monitored in the modern lake (Zolitschka et al., 2006; Mayr et al., 2007b) and selected results from previous investigations that according to Fenchel (1999) are relevant for this study. Our data suggest that oxygen penetration in the sediments is very limited generating dysoxic conditions. However, previous investigations based on bulk elemental ratios by Haberzettl et al. (2007b) indicated prevalent oxic to suboxic conditions at the water/sediment interphase. Only a direct monitoring of this parameter will provide the necessary dataset to clarify this question.

Gravity core 5022-1J was retrieved from the center of the lake at 100 m water depth (Fig. 1) during the PASADO drilling campaign and immediately sampled in the field for geomicrobiological studies. Core PTA 02/4 was previously retrieved in a comparable location from the deep central basin of Laguna Potrok Aike (Fig. 1, Haberzettl et al., 2005) providing a well-dated paleoclimatological record. An excellent correlation between the latter and core 5022-1J was accomplished using cluster analyses on pollen and diatoms and DGGE profiles, respectively, allowing a direct comparison of paleoclimatic and geomicrobiological proxies.

3. Sampling and methods

3.1. Field sampling and handling

Two cm long and three cm wide windows were precut in a core liner every 5 cm and subsequently closed with strong adhesive tape prior to coring (Fig. 2). Samples were numbered S1 to S19 and regularly spaced corresponding from 5 to 95 cm sediment depth.

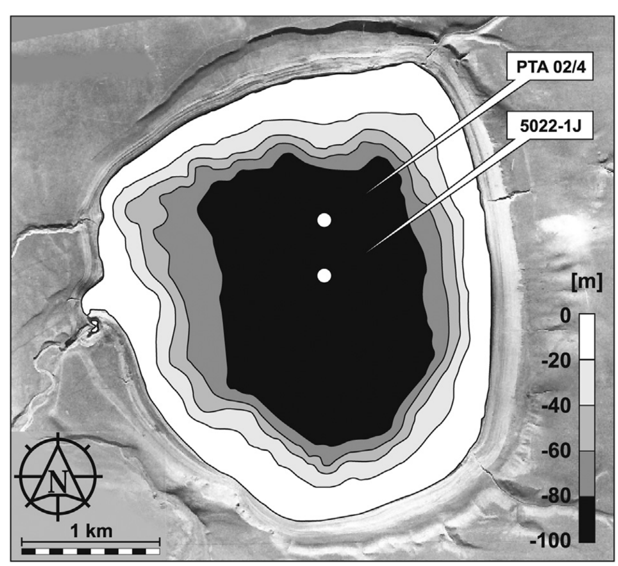

Fig. 1. Bathymetric map of Laguna Potrok Aike (modified after Zolitschka et al., 2006) showing the positions of the two gravity cores studied in this paper.