Paleohydrology record of the stromatolites of the Bacalar Lagoon: new insight for climate change assessment in the Mexican Caribbean

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ABSTRACT

Microbialites have played an important role in the early history of life in the Earth, their growth depends on the physic-chemical conditions of the water, due to this it is possible related the environmental conditions to the sedimentary record. The Bacalar lagoon is one of the largest freshwater microbialite (stromatolites) occurrences in the world, with variable morphologies in different parts of the lagoon due to the dynamic and composition of the lagoon. The Bacalar lagoon is facing to anthropogenic activities derived from the tourism and agriculture, the changes in the composition of water column derived from these activities and the natural changes from the system will be record in this work.

INTRODUCTION

The stromatolites are organosedimentary carbonate deposits formed from the interaction between benthic microbial communities and detrital sediments; their growth is influenced by local climate changes and other environmental factors as dynamic of the system, depth changes, direction of light, substrate, etc. (Castro et al., 2014; Dupraz et al., 2011). The structures preserve the physicochemical conditions of water in which they deposit, for that reason the stromatolites are consider as a great proxy to make a hydrologic reconstruction (Dickas, 2015; Woo et al., 2004; Riding, 1999, 2000; Kendall &Mcdonell, 1998).The paleohydrological reconstructions let us to know the dynamic and composition variation of different water systems through the time. Due to the difficulty to have a directly record of the hydrologic past conditions it is necessary to use indirect proxies, in the sedimentary record there are both biological (fossil) and non-biological (isotopic signals) proxies (Wefer et al., 1999; Lowe & Walker, 1997). The stable isotope analyses in the sedimentary record of stromatolites reveal information about the temperature and geochemical composition of the water (Andrews, 2006) like carbonate and trace element content (Stumm, 1992). The stromatolites growth in specific conditions of light, pH, depth, temperature, nutrient content, waves and currents, etc., this is why it is possible to link the environmental conditions with the lithological parameters in a paleohydrologic record (Beraldi, 2014; Duprazetal., 2011).

The Bacalar lagoon carbonate structures are unique because they are one of the largest freshwater microbialite occurrences in the world (Centeno et al., 2012; Gischler et al., 2008), and because they preserve past information about the climatic and life conditions during sedimentation process. Like other karstic systems as Cuatro Cienegas Lagoon, Shark Bay, Pavilion Lake, Van lake, etc. (Gischleret al., 2008), the Bacalar lagoon has carbonate structures (stromatolites), with 10 km extension along the western part. The presence of these structures is related to carbonates concentration and lagoon dynamic. The western part of the lagoon is directly connected to the sinkholes and the aquifer, this interaction results in high carbonates concentration compared to the whole lagoon. Likewise, the interaction and the dynamic between the lagoon and the aquifer are some of the physic processes that can lead to the stromatolites growth. In the narrowest part of the lagoon, called “Los Rapidos”, the flow rate is the highest, inducing a water mix, nutrients and carbonates concentrations increases, and the stromatolites tend to growth also (Castro et al., 2014; Babel et al., 2011; Gischler et al., 2011).

The Bacalar lagoon ecosystems need a protection, governance and policies in adaptation/resilience programs facing to climate change. To define policies based on scientific research, using ancient structures like stromatolites as proxies, to explain the past and to help us to answer the present challenges, and to visualize the future transformations, it is fundamental in order to make decisions and take action about the management of the coastal lagoon in the Mexican Caribbean.

Through this investigation it could be seen the changes in the composition and dynamic of the lagoon, and the results can let to make some projections (climatic, recharge and anthropogenic). A paleohydrological reconstruction can be done with the analysis of sedimentary record of these structures, in order to know how the Bacalar lagoon have changed through the time, in terms of the chemical composition, changes in temperature and precipitation (climate change), and due to groundwater contribution and other factors.

SETTING

The Bacalar lagoon (LB) is located in Southeastern Quintana Roo, Mexico (18°40'47'' N, 88°23'05'' W, 1.5 m.a.s.l.) (Fig. 1). The lagoon has 3.1 km^2 surface area, 40 km long, and 1 to 2 km wide (Castro et al., 2014; CONAGUA, 2002). The BL has a tectonic origin, as part of the Rio Hondo fault zone, which was created over the Miocene; the fault system is result of distinct tectonic event over Late Cretaceous to Pliocene times (Bauer et al., 2011; Díaz, 2005; Beddows, 2004). Derived from the formation of lacustrine deposits, the BL is composed by limestones and loams mainly (Sánchez et al., 2015). The lagoon is an oligotrophic system, with 15 m maximum depth and the presence of seasonality is low, the temperature during the winter is ~28°C, while in the summer is ~29°C. The lagoon is a freshwater system (conductivity of 0-2.3 mS/cm), a pH between 7.6 and 8.3 (Beltrán, 2010). The climate of the study site is humid subtropical modulated by two meteorological processes, the first constituted by the cold fronts, locally named "Nortes", present during the winter and the dry period present from March to May. The second meteorological process is the tropical storms with rainfall events (900 mm/year), and hurricanes. The rainy season is between June and September (1250-1500 mm/year) (CONAGUA, 2015).

The Bacalar Lagoon is located in the hydrologic region No. 33 (RH33), over a karstic platform, with five sinkholes in the west part of the lagoon with ~90m depth, three (Cocalitos, Esmeralda and Negro) are inside the lagoon with surface connection, the Cenote Azul only has an underground connection. The Xul-Ha sinkhole is connected to the lagoon through a channel (Gischleret al., 2011; Pérez, 2011; Beltrán, 2010; Perry et al., 2009). The eastern part of the lagoon is connected with the Chetumal Bay through the Rio Hondo, and to Chile Verde and Guerrero lagoons (Fig. 1). The water table variation of the lagoon was estimated in ~30 cm (Gischler et al., 2011).

The Bacalar town has become a municipality three years ago only, and the plans for urban development, and tourism (infrastructure and activities) investments are causing a pressure over these ancient structures and over the symbolic lagoon, locally called "Seven colors Lagoon". Due to the lagoon landscape nature, the main economic income of the population comes from the tourism. However, the increasing tourism and associated water activities in the lagoon (some of them not properly regulated), are causing a negative impact in the ecosystem, particularly in the stromatolites (Diaz, 2005). The Bacalar lagoon does not have a regulation like protected area, and the development plan is been evaluated. The main activities of the area are agriculture (sugar cane, rise and maize), livestock (cattle porcine and ovine), and beekeeping (Díaz, 2005; INEGI, 2002).

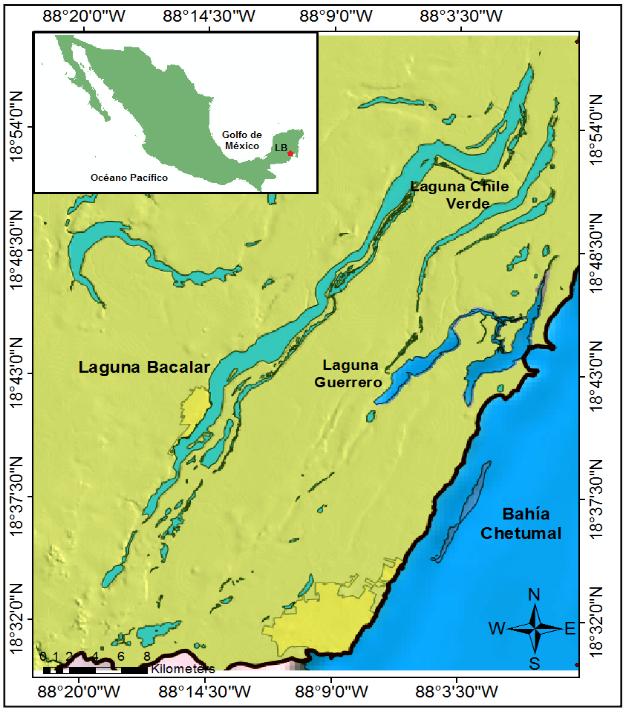

Figure 1. Bacalar Lagoon location

METHODS

Sampling sites

Three transects were defined, and six sites selected to collect water samples, lacustrine sediment and stromatolites cores. The sampling campaign was conducted in November 2016. The water samples were collected for nutrients (NH_4, NO_2, NO_3, PO_4) analysis, the samples were filtered with 0.45 μm syringe filter and collected in 125 ml polyethylene bottles (Nalgene®), previously washed with HCl, according to the Standard Methods procedure (USGS, 2015; APHA, 1998).

Besides, in polyethylene bottles (Nalgene®) were collected 250 and 125 ml water samples for alkalinity and anions analysis respectively. The bottles were previously washed in 14% nitric acid (HNO_3), while the bottles for cations (125 ml) were washed in HCl to avoid cross contamination. Each sample was sealed, labeled and kept in a cooler at 4°C, and transported to laboratory for the analysis.

Analyses *in situ*

The temperature, pH, depth, total dissolved solids (TDS), conductivity and dissolved oxygen were measured in the field with a multiparametric sonde YSI®, model 6600. The parameters were measured near the stromatolites formations. The morphology of stromatolites was determined in the field; the selected stromatolites structures were measured avoiding any damage.

Laboratory analysis

To water characterization, alkalinity, nutrients, major and trace elements concentration were determined in the collected samples, as well as the isotopes ^{18}O, ^{13}C and U/Th datation. The alkalinity was measured by the titration method, using acid sulfuric (H_2SO_4) with a concentration of 0.2 N. The nutrients determination (NO_3^-, NO_2^-, PO_4^{3-}), cations (Ca^{2+}, Na^+,Mg^{2+}, K^+, Sr^{2+}) and anions (Cl^-, SO_4^{2-}) were determined by ion chromatography, using an 882 Compact Plus IC Metrohm®. For the NH_4^+ determination a spectrophotometer LaMotte® was used. The laboratory analyses were performed at the Hydrogeochemistry and Water Quality Laboratory of the Water Sciences Unit, CICY A.C.

Stromatolites and sediment samples

The stromatolite cores were collected in the western part of the lagoon with a push core of 5 cm diameter and a length of 11-40 cm. In addition, lacustrine sediments cores were collected with plastic liners of 5 cm diameter and 11-43 cm length (Fig. 2). Each core was kept in a cooler at 4°C and transported to Water Sciences Unit laboratory.

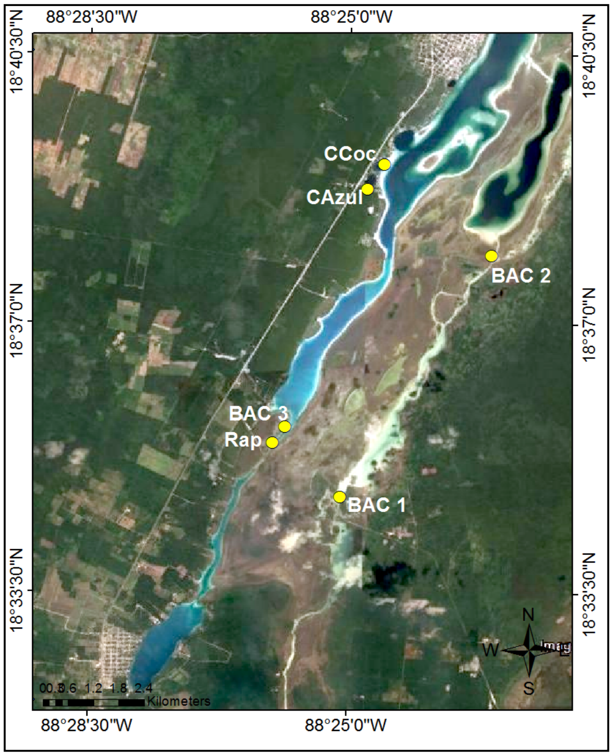

Figure 2. Sampling sites location (yellow points)

The cores (lacustrine sediment and stromatolites) were splited every 5 cm for stable isotopes of ^{18}O and ^{13}C, and trace element analyses. The samples were dryed at 50ºC, and grinded with an agate mortar. For isotopes analysis a sub-sample was selected, and the organic matter was eliminated, adding H_2O_2 50%, during 48 hours, the remaining sediment was rinsed with MilliQ water and drying at 50 ºC. To establish the chronology of the lacustrine sequence, the cores were dated through accelerator mass spectrometry (AMS) ^{14}C at the Marine Sciences Laboratory of the University of California Santa Cruz. To identify the input of terrigenous at the lagoon the changes in magnetic susceptibility was record at the Geophysics Institute of the UNAM.

RESULTS

Water

The temperature profiles along the lagoon were not variable indicating that the lagoon in very homogeneous, due to the depth is very low (15 m) and permit the water mix (Fig. 3). Only in the sinkholes temperature profiles were observed a thermocline around 23m (Fig. 4).

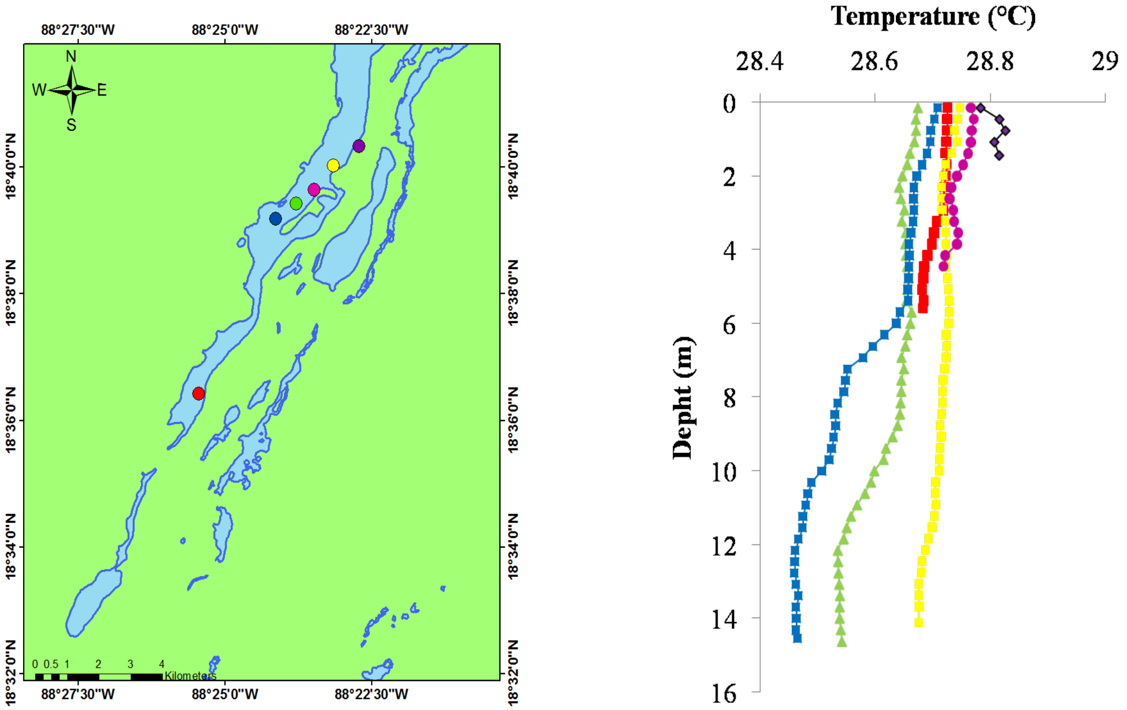

Figure 3. Temperature profile along the lagoon (left, point sites of profiles; right, profiles with respective color of sites in the left picture)

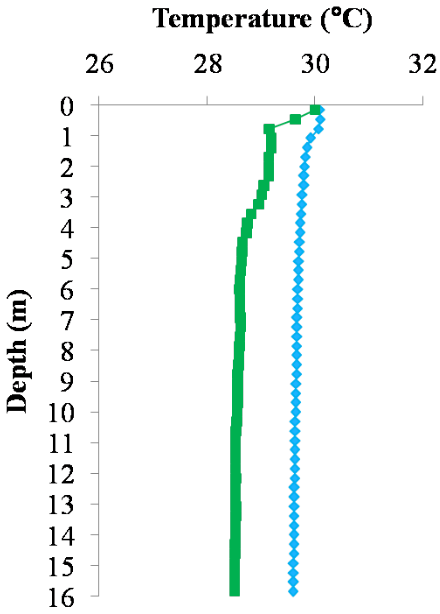

Figure 4. Temperature profiles of cenotes (green: Cocalitos; blue: Cenote Azul)

The values of alkalinity in the west part of the lagoon were greater (more than the average of the sea 140 mg/l) than the samples taken in the east part. This values show that there is an inflow of water enrich of carbonates. The nitrates concentrations and TDS were very homogeneus in all the sites, while the nitrites and phosphates were lower to the limitis of detection of the chromatographer (<1 ppb).The values of chlorides and sulfates are greater in the east part, while the western are lower, due to the proximity to the sea.

Sediments

Lacustrine Sediment core description

Rap	Total length of 11cm, the surface was green with a little brown, and the grain size was variable sands, the surface part has more big size and contains some green rocks. The last cm has very fine coffee color sediment, and the presence of matter organic.
CCoc	36 cm length, the first 3 cm are grey darker than the rest of the core. The presence of red plants remains are observed in the entire core.
BAC 1	27 cm length, grey color core, except the first 5cm (brown). Throughout the core plant remains are observed, maybe part of mangrove.
BAC 2	43 cm length, the first 5 cm are green, the middle core is brown, and the last 8 cm are grey with fine grains as silts.
BAC 3	19 cm length, very fine sediments, the last 12 cm are finer than the rest of the core. In general, the core is brown, with a grey color at the lower part. The surface sediment is green maybe to the presence of cyanobacteria.

Stromatolites core description

Rap	The total length is 10 cm, the size grain is variable but the last 4 cm are finer. The core is between green and brown and there are present some green rocks. In the base of the core organic matter is observed.
CCoc	The total length is 20 cm, the upper part is green and the rest is brown, there are present a lot of bivalves fragments, the sediment is sandy but in the last part the sandy is thicker. In this core it was observed the presence of mollusks that could indicate the presence of some contaminants.
BAC 3	The total length is 40 cm, the first 5 cm are green and the rest of the core is brown and the base is grey. The sediment is sandy, however as the depth increases the grain size too. In some parts of the core it is observed some mollusks.

CONCLUSION

The stromatolites of the Bacalar lagoon show that the morphology of these structures depends on the dynamic and composition of the lagoon. The zone of Los Rapidos (Rap) and BAC 3 has the highest stromatolites due to the flow of the water is greater than the rest of the lagoon and this promoted the water mix and thus the increment of the nutrients. In addition, in the western part of the lagoon, the carbonates concentrations are greater than in the eastern part, suggesting a groundwater inflow.

This lagoon could have some changes in its composition due to human activities, this because in the place it is observed that some of the stromatolites are affected by boats, trash, waste water, etc., for that reason it is necessary to implement some security politics to prevent the damage of the stromatolites.

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