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Late Holocene mangrove development and onset of sedimentation in the Yax Chen cave system (Ox Bel Ha) Yucatan, Mexico: Implications for using cave sediments as a sea-level indicator

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ABSTRACT

This study examines the relationship between the flooding of cenotes and formation of coastal mangrove with Holocene sea-level rise and the onset of aquatic sedimentation in Yax Chen, a cave system in Quintana Roo on Mexico's Yucatan Peninsula. Sediment depth measurements ($n = 180$) were collected along 2.7 km of an underwater cave passage and three cores were radiocarbon dated to examine both the extent and timing of sedimentation in the cave. Basal radiocarbon ages (~4 Ka) for aquatic sediments in the cave show that Holocene sea-level rise flooded cenotes, creating sunlit open water conditions with associated mangroves on the upper karst surface. These conditions initiated abundant and widespread sedimentation in the cave. Cenote surface area controlled the long-term sediment accumulation in the cave passages through primary productivity in the sunlit open water areas of the cenotes. This primary productivity was enhanced with mangrove formation, which causes funneling of precipitation and nutrient-rich waters into the cenotes from the mangroves. Accumulation histories from the radiocarbon-dated sediment cores ($n = 3$) were compared with accumulation histories in previously published studies including Actun Ha, Mexico and Green Bay Cave (GBC), Bermuda.

1. Introduction

Cave and sinkhole sediments have been used to document water level changes in anchialine systems and can be used as a proxy for sea level (Gabriel et al., 2009; van Hengstum et al., 2011, 2015). However, many of these studies were based on limited datasets or are speculative, as there are few studies which provide a basis for comparison. Recent research in Yax Chen (part of the Ox Bel Ha cave system) and the Outland Cave in Quintana Roo, Yucatan Peninsula, Mexico show that sedimentation can be ephemeral and non-continuous in cave passages (Collins et al., 2015a, 2015b). The study from the anchialine system of Sac Actun (Outland Cave) demonstrated the difficulty of reconstructing water levels and inferring sea level from cave systems with an upper karst terrain dominated by tropical forests (Collins et al., 2015a). The study emphasized that not only bottom elevation but more importantly ceiling elevation can control sedimentation in the cave. Research using sediment traps in Yax Chen showed the role of mangroves and cenote area on the sediment flux in downstream cave passages (3 years of data; Collins et al., 2015b). Little sediment was found in upstream cave passages dominated by tropical forest vegetation, while passages with overlying mangrove and large cenotes had abundant sediment. This study further examines long-term sedimentation patterns (1000s of years) in Yax Chen and the role of Holocene sea-level rise and mangrove formation which has important implications for using cave sediments as a sea-level indicator (van Hengstum et al., 2015).

1.1. The caves of Quintana Roo, Mexico

The Yucatan Peninsula is a carbonate platform of Paleogene to Quaternary age which has undergone multiple phases of diagenesis altering mineralogy and textural characteristics (Weidie, 1985). However, the platform has largely retained its sub-horizontal geometry with minimal differential tilting (Weidie, 1985; Coke, 1991; Beddows, 2004). The caves in the Yucatan have formed through repeated cycles of vadose and phreatic conditions associated with sea-level fluctuations over the Quaternary (Smart et al., 2006). The limestone matrix has a porosity of 17% but there is also a large anastomosing network of caves passages (>2 m dia.) with smaller hydrologic pathways through fractures and bedding planes (Beddows, 2004; Smart et al., 2006). Cave passage formation has been attributed to Mixing Zone (MZ) dissolution that occurs at the transition

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between saline and meteoric groundwater which is undersaturated with respect to $CaCO_3$ (Back et al., 1979, 1986; Hanshaw and Back, 1980; Beddows, 2004; Smart et al., 2006; Werner, 2007).

Cenotes form during sea-level low-stands when the weight of the ceiling exceeds the flexural strength of the limestone causing collapse resulting in a central breakdown deposit at the bottom of the cavern (Finch, 1965; Smart et al., 2006). The central breakdown deposit consists of angular, brecciated limestone boulders strewn on the floor of the cave. Cenotes (or sinkholes; karst windows) provide openings to the cave passages and act as point sources for allogenic sediments entering cave passage downstream (Pohlman et al., 1997; Gabriel et al., 2009; van Hengstum et al., 2010, 2015; Collins et al., 2015b). Organic matter (OM) and phytoplankton (e.g. diatoms) sediment enter the cave passages largely through this cenote point source as there is no primary productivity in the dark cave passages (Pohlman et al., 1997; Benavente et al., 2001; van Hengstum et al., 2010). Other allogenic sediments found in the cave system includes detrital carbonate (percolation from ceiling), transported speleothem fragments and minor clastic aeolian-derived dust (Schmitter-Soto et al., 2002; Lopez Fuerte et al., 2010; Collins et al., 2015a, 2015b). Autogenic sources of sediment are limited and include chemical precipitates such as calcite rafts, gypsum and chemoautotrophic microbial mats. Sediment can also enter through cracks and fissures in the bedrock but is minor in comparison to the cenotes (Mazda et al., 1990; Wolanski et al., 1992; Pohlman et al., 1997; Simon et al., 2007). Modern sediment trap studies in Yax Chen found a correlation between cenote area and mangrove extent with the amount of sediment entering the cave (Collins et al., 2015b).

1.2. Hydrogeology

The Yucatan has limited surficial water as the limestone has a high matrix porosity (~17%) with most of the water stored in the subsurface (>96%) and the cave passages accounting for ~99% of groundwater flow (Beddows, 2004). Due to this high porosity, water table elevation approximates sea level and there is minimal hydraulic gradient (10^{-5}), which equates to a water table rise of 1–10 cm/km (Beddows, 2004; Bauer-Gottwein et al., 2011; Milne and Peros, 2013; van Hengstum et al., 2015).

Groundwater in the Yucatan is density stratified with a meteoric lens (ML) on top of saline groundwater (marine water mass, MWM). Density contrasts between the warmer, denser MWM (~35 PSU) and the cooler ML (PSU < 1) are responsible for the stratification (Moore et al., 1992; Neuman and Rahbek, 2007). In Yax Chen, the MZ between the ML and MWM ranges from 10 and 14 mbsl and is stepped (~6–35 PSU; Collins et al., 2015b). The MZ can demonstrate changes in temperature, pH, dissolved oxygen and salinity depending on the location in the cave and the time of year (Esterson, 2003). There are numerous controls on the thickness and position of the MZ. Large-scale changes are a result of eustatic sea-level fluctuations. As sea level rises and falls, the aquifer tracks these changes and the MZ moves coincidently (Back et al., 1986; Raeisi and Mylroie, 1995; Florea et al., 2007). Short-term fluctuations in position and thickness of the MZ in the cave are a result of flow velocity changes, channel morphology and sinuosity of the cave passage (Smart et al., 2006; Beddows et al., 2007). The majority of mapped Yax Chen cave passages are within the ML (i.e. <10 mbsl).

Groundwater flow in Yucatan anchialine caves is low but varies with distance from the coastline with velocities ranging from 12 cm/s on the coast to ~1 cm/s 10 km inland (Moore et al., 1992). Cave passage morphology, flow patterns (Reynolds number) and sediment density can control patterns of sedimentation on the cave bottom (Beddows, 2004). The geometry of the passages are elliptical tubular, irregular and often subject to sudden elevational changes and abrupt bends (Smart et al., 2006). In addition to the changes in the shape, cave floors and ceilings tend to be obstructed with stalagmites, stalactites and central breakdown deposits, which can affect the rate and Reynolds

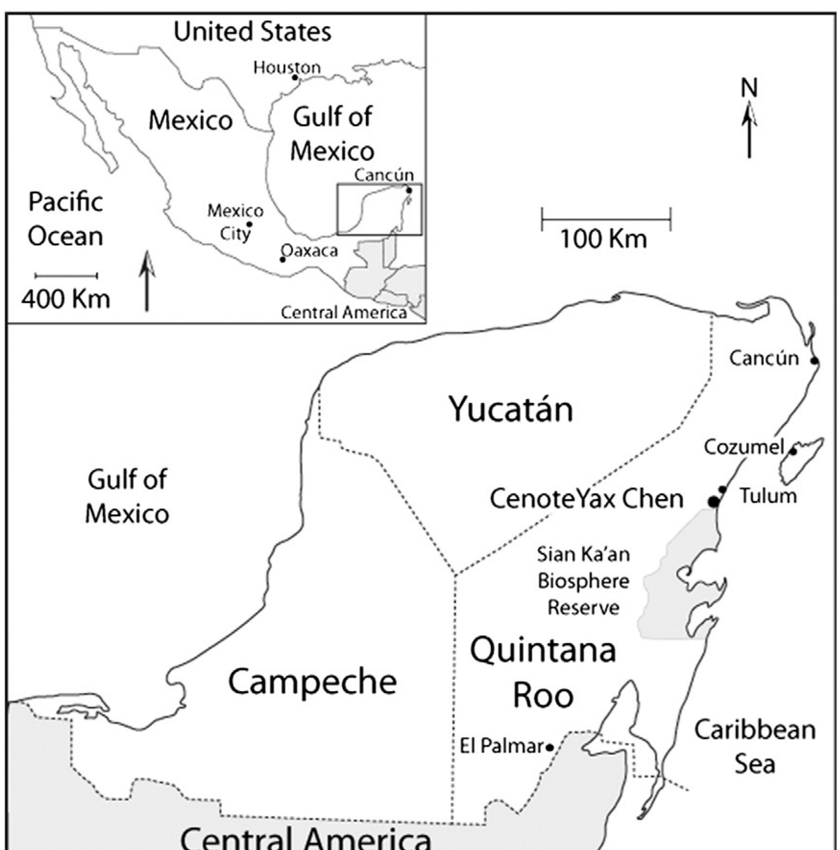

Fig. 1. The location of Cenote Yax Chen on the Yucatan Peninsula, Mexico.