Shallow Speleogenesis in a Coastal Carbonate Platform: Quintana Roo, Mexico

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Abstract

Many existing models of speleogenesis in carbonate platforms assume extensive cave development occurs at the freshwater and saltwater mixing zone, and that cave formation occurs most readily along the lower boundary of the mixing zone. In Quintana Roo, Mexico, extensive underwater caves are coincident with the modern mixing zone, and equally extensive dry caves occur at or above modern sea level and above recent sea-level high stands. We hypothesize that mixing-dissolution alone is insufficient to explain the location and extent of observed dry cave passage, especially given the relatively brief periods of time at which these elevations could have been in a mixing zone. Other mechanisms, namely inputs of soil CO_2 along the water table, and aquatic microbial influences, merit further investigation. Both the amount of time spent at each sea level and the past climate control the volume and rate of conduit formation. Existing sea level records and proxies suggest that the water table has not been at or above modern sea level long enough to produce the caves we observe. In order to better constrain the timing of cave development, U-Th dates will be obtained from speleothems and folia in dry caves. Narrow zones of folia are laterally extensive in some sections of the caves and are assumed to represent calcite deposition at an ancient water table under tidal influence.

Preliminary U-Th ages obtained from one stalactite in Jaguar Claw Cave yields an age of ~252 ka BP, and folia overgrowth (~7.2m above modern water table) of ~49 ka BP. Current sea level proxies suggest that the latter was a time of sea level low stand (-40m). Folia from another sample ~1.4m above the water table indicate that a sea level high stand occurred ~251 ka BP. If supported with further data, this may be the first record of a high stand at these times recorded in the Caribbean, and suggests that sea level curves for the Yucatan Peninsula require some revision.

Site Location

The Yucatan Peninsula epitomizes a coastal karstified carbonate aquifer, and the eastern coast contains what may be the most extensive cave system in the world. The platform has remained tectonically stable since the late Pleistocene, making it an ideal location to use as a model system.

Fig. 1

Fig. 1: This carbonate platform originated from deposition in shallow to deep marine environments present from the Paleozoic through the Holocene that formed a carbonate sequence >1,500 m thick, below which lie basement volcanic rocks (Smart et al., 2006). Formations exposed at the surface range in age from the oldest, Eocene-age rock at the center of the platform to the youngest, Holocene-age rock at the coastline. Strata are generally flat-lying, resulting in a nearly level topography across the entire peninsula.

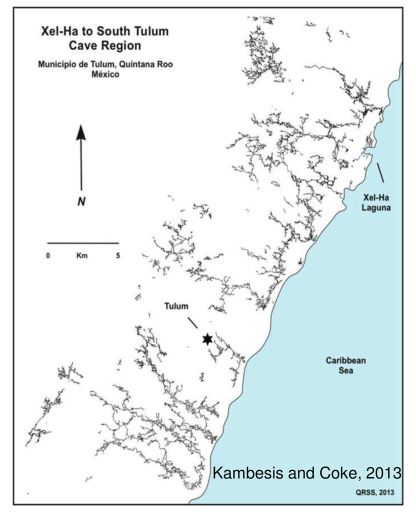


Fig. 2

Fig 2: A combination of high inland recharge, diagenetically immature carbonates, intersection of regional fault and lineament trends, and mixing zone dynamics have formed a shallow, density-stratified coastal karst aquifer drained by a vast network of conduits (Kambesis and Coke, 2013). Since the 1970s, over 1,200 km submerged caves have been surveyed within 10 km of the Caribbean coast between Puerto Morelos and Tulum (AMCS). This includes the systems Sac Actun (333 km) and Ox Bel Ha (244 km), which are respectively the second and fourth longest cave systems in the world. About 300km of dry passages have been surveyed in the last 10 years, with exploration continuing at a fast pace. A vast majority of all surveyed caves are found at or above the modern mixing zone.

A Process Model of Coastal Speleogenesis

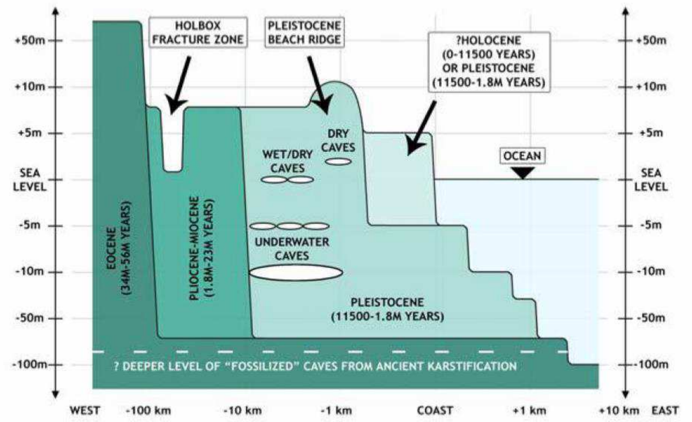


Fig. 3

Fig. 3: Mixing dissolution along the base of the freshwater lens results in tiers of conduit development coincident with time spent at former sea levels. Caves can also form along the top of the water table where meteoric water infiltrates and mixes with groundwater. As sea level changes, older conduits provide flow pathways and become submerged, resulting in overprinting of periods of deposition and dissolution. The location of caves relative to the modern mixing zone does not necessarily reflect their origin.

Fig. 4A

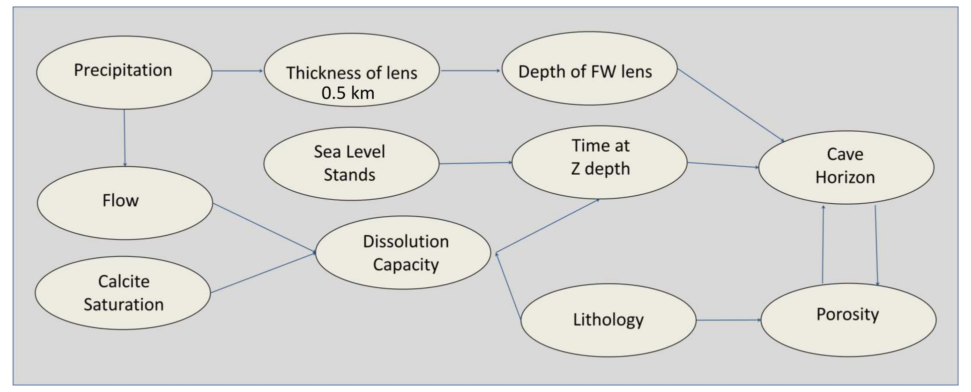


Fig. 4B

Fig. 4A and 4B: Caves in Quintana Roo contain large volume passages within a few meters of the surface. The depth and extent of cave development is influenced by many factors, including water chemistry, lithology, geologic structure, and recharge volume. To effectively forward model secondary porosity, each of these factors must be identified and their interactions understood. A simple model quantifying these process will be used to test hypotheses about the rates and origins of speleogenesis. Ultimately, the total rate of dissolution and the time spent at a particular sea level will determine the depth of a cave horizon.

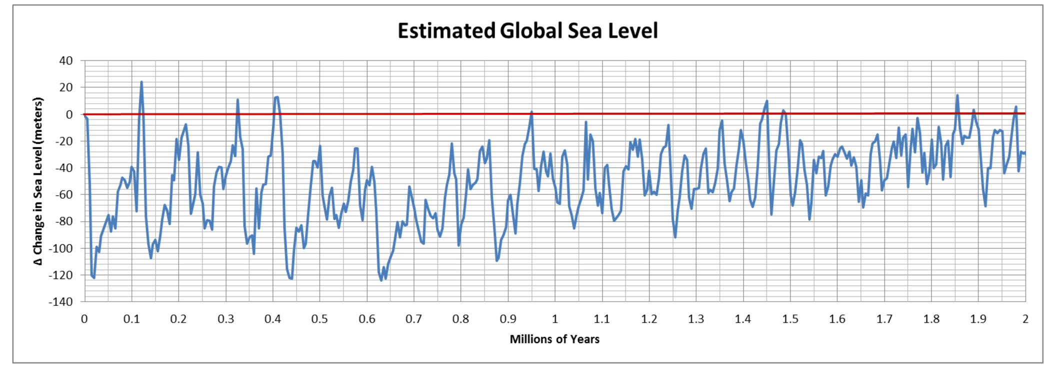


Fig. 5

Fig 5: The Yucatan Peninsula has been subaerially exposed for approximately 2my. A review of global sea level history across that time period indicates that the cumulative time spent at or above modern sea level is relatively short.

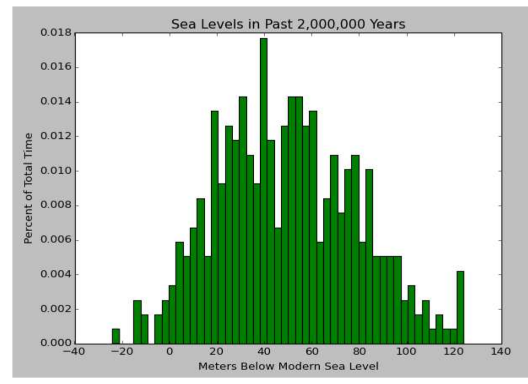


Fig. 6A

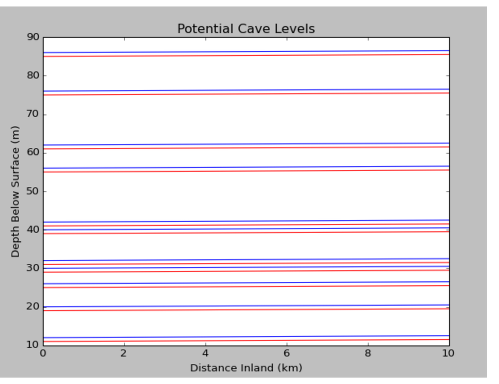


Fig. 6B

Fig 6A and 6B: A preliminary model using Python estimates depth intervals with the potential to contain 1m wide conduits based on cumulative time spent at different sea levels, with an assumed dissolution rate of 0.1mm/year and a groundwater gradient of 0.7m/km

If caves form most rapidly at the base of the freshwater lens, then extensive cave horizons should be found much deeper. In Quintana Roo, most surveyed caves are between 0 to -20m, which may reflect accessibility bias. Some deeper caves are known, and deep pits appear to play a significant role in groundwater circulation (upwelling) as far inland as 10km. The origin of deep and shallow caves in Quintana Roo is likely different. The extent of observed shallow caves exceed what is expected from dissolution alone. Other processes, namely soil derived CO2, merit further investigation.

U-Th Dating for Timing of Sea Level Stands

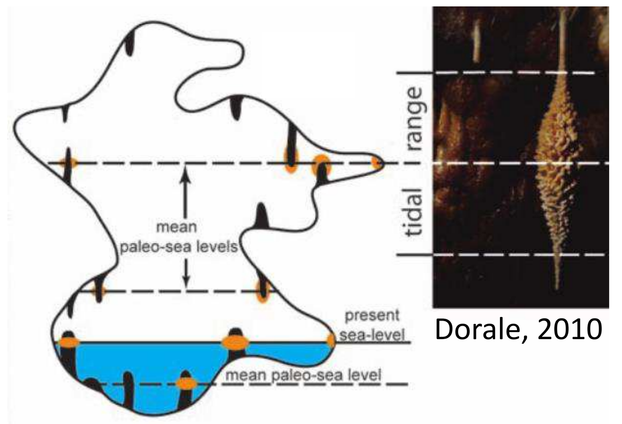


Fig. 7

Fig 7: Phreatic overgrowths on speleothems (POS) develop as calcite crust forms at the surface of the water table where supersaturated water fluctuates over a tidal range. Calcite deposits on the surface of stalagmites and stalactites provide a record of former water table elevations, which correspond to former sea levels. Unlike coral, which has a lag time in growth, POS form extremely rapidly, and therefore serve as high resolution proxies for sea level history. Sea level stands missing via other proxies can be identified from POS in tectonically stable coastal karst regions.

Fig. 8A and 8B: POS now in dry cave passage (8A) indicate past water table elevations higher than today, and submerged POS (8B) correspond to lower elevations. Clean $CaCO_3$ deposit contains measureable amounts of ^{234}U & ^{230}Th, but negligible amounts of ^{232}Th, allowing precise analysis for U-Th dating.

Fig. 8A

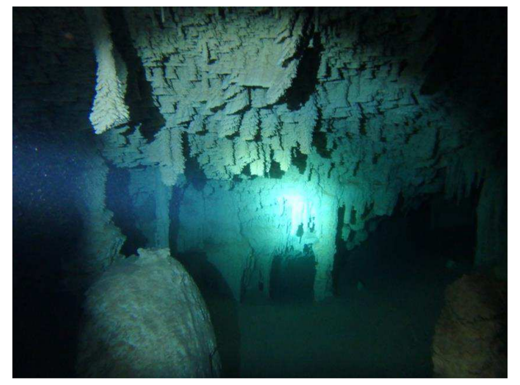


Fig. 8B

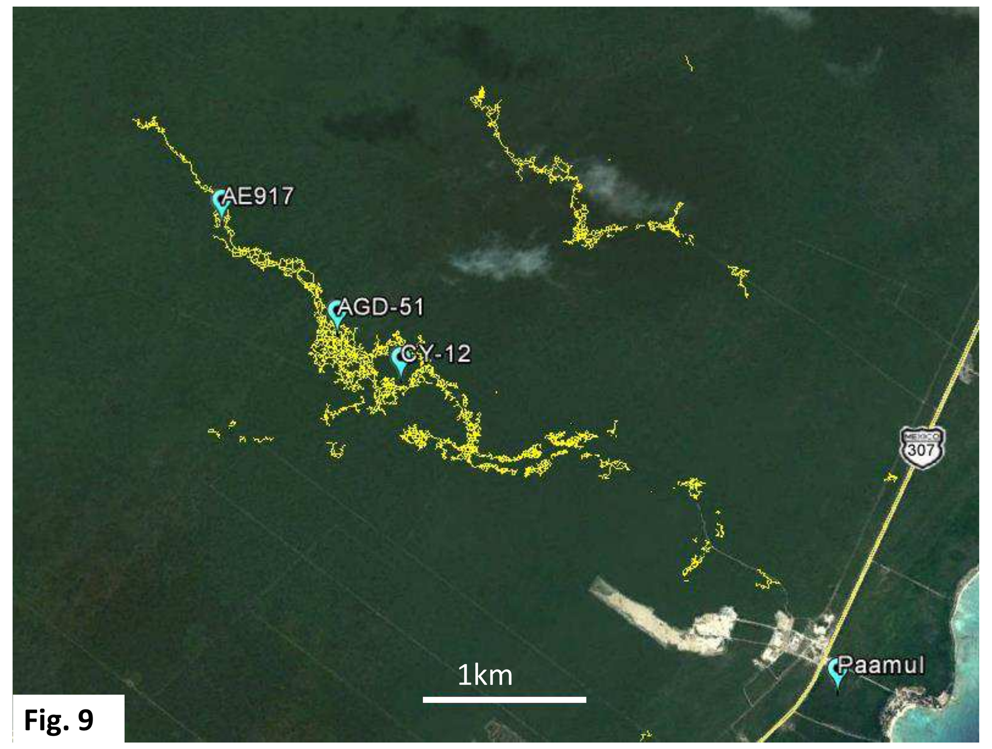
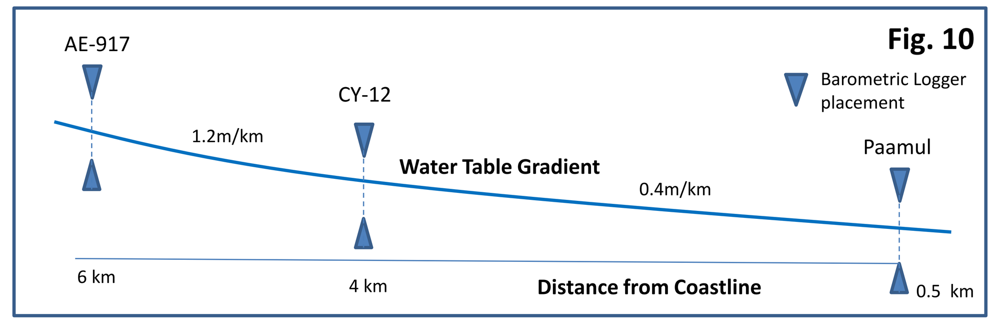


Fig. 9

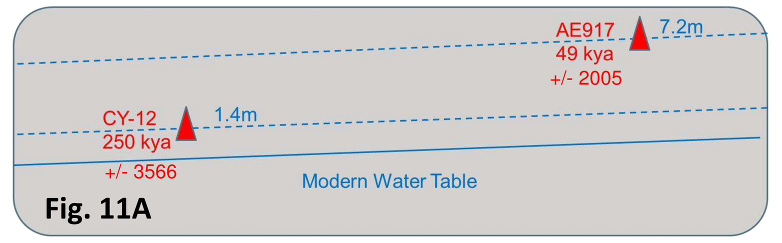
Fig 9: POS were collected from two locations in Jaguar Claw cave system in Paamul, Quintana Roo, MX. This cave provides access to a transect of the water table perpendicular to the coastline. The first site, CY-12 (Turtle Lake) is 4.03 km inland. The second site, AE917 (Jaguar Claw) is 5.88 km inland. Both samples contained a stalactite in the center covered with overgrowth, and both were collected in what is now dry passage. Collections from AGD-51 were obtained in December 2016 and are awaiting U-Th analysis.



Samples were surveyed to the surface of the water table. The water table gradient was measured at each site and monitored for one year to observe tidal and seasonal ranges.

Fig 10: The modern water table gradient averages 0.7m/km. Tidal signal showed a delay of about 4 hours 6km inland with amplitude attenuation from 40cm to 4cm. The gradient did not vary significantly across the dry and wet seasons. Former gradients could be determined from obtaining POS of the same age at similar elevations.

Evidence of Rapid Sea level Change



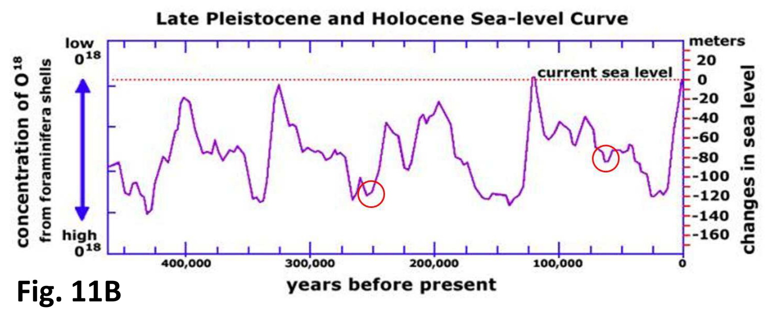


Fig. 11A and 11B: POS record highstands at 49kya and 250kya respectively. This is the first time that these highstands have been noted in the Yucatan Peninsula. Evidence for a highstand at 49kya has been noted in the Bahamas (Mylroie, 1988). Due to the relatively rapid formation of POS, these high stands were likely brief, and suggest a sudden rise and fall in sea level. Additional samples from a range of elevations at the same sites have been collected to constrain the duration of these events.

Ages of the interior speleothems were (CY-12) 338 kya +/- 6500 and (AE-917) 252 kya +/- 2200, both of which are consistent with lowstands occurring during those times.

Anticipated Results

If mixing-zone dissolution is the dominant conduit-forming process in Quintana Roo, then tiers of cave development are expected to correspond to periods when sea level remained stable for significant lengths of time. Shallow cave development is likely a result of processes other than mixing dissolution alone, based on the known sea level history of this area. Dry cave passage appears to follow the gradient of the top of the water table. Sea level curves require some revision based on evidence of short-duration highstands.

Application

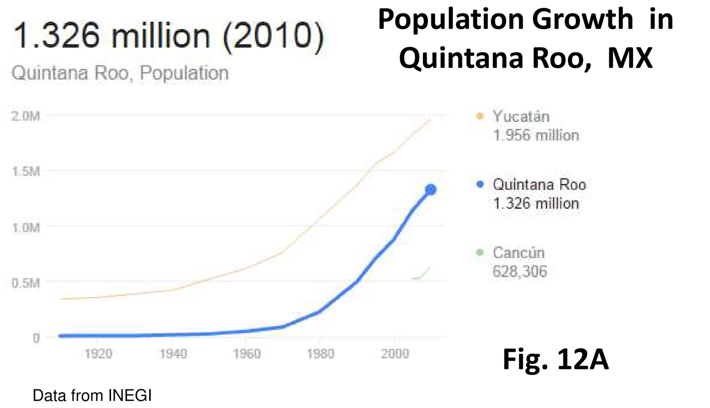


Fig. 12A

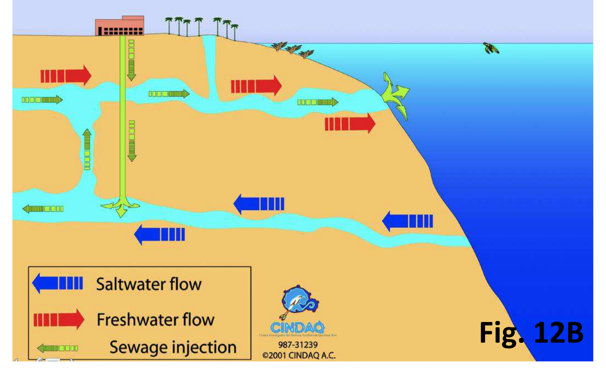


Fig. 12B

Fig 12A and 12B: The rich ecological setting of the Yucatan peninsula has made it a popular tourist destination and consequently the area has experienced intense population growth (12A). Growth continues to outpace needed infrastructure, while environmental policy is either lacking or poorly enforced. A major concern is the disposal of wastewater, which is often pumped directly into the water table where it may recirculate and contaminate the drinking supply (12B). This study will provide more accurate characterization of secondary porosity to inform regional-scale groundwater models.

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