Modeling Speleogenesis and Aquifer Development in a Coastal Carbonate Platform: Quintana Roo, Mexico

Aubri A. Jenson[1], Benjamin F. Schwartz[1,2]

[1]Department of Biology, Texas State University, San Marcos, Texas

[2]Edwards Aquifer Research and Data Center, Texas State University, San Marcos, Texas

Abstract

Mixing-zone speleogenesis is generally assumed to dominate conduit development in carbonate platforms. However, both mixing zone and vadose CO_2 reactions contribute to cavernous porosity, and mixing-zone dissolution alone does not adequately explain patterns of cavern development that are observed in many systems. Horizontal and vertical bedrock heterogeneity, and a mixing zone that moves with sea level, complicate efforts to understand linkages between geologic, hydrologic, and geochemical controls on aquifer development. Ultimately, models of carbonate platform speleogenesis must include interactions between all of these parameters over time and space. The objective of this project is to create a model that simulates patterns of cave development observed along a 100km stretch of the eastern coastline of the Yucatan peninsula in Quintana Roo, Mexico.

In the last 2 million years, sea-level has fluctuated between -120m and +6m relative to modern sea level. If cave development is primarily controlled by the position of the freshwater-saline water mixing zone, then conduit horizons should be coincident with past locations of the mixing zone, the depth of which increases with distance inland. Over 150km of passage have been mapped above current sea level within 10km of the modern coastline, and mapping continues inland in the shallow subsurface. Many of these conduits are 9-12m above modern sea-level, which suggests that alternative modes of speleogenesis such as soil-derived CO_2 need to be considered. While the majority of underwater conduits are found between -10 and -30m, no extensive conduit network is known that corresponds with cumulative stillstands at depths near -50m, suggesting that alternative controls influence cave development at different depths.

Research Objectives

1 - Vadose Zone: Assess the extent of inland cave development and develop a conceptual speleogenesis model that considers vadose and soil CO_2 in addition to mixing dissolution.

2 - Modern Mixing Zone: Identify the geochemical and structural controls on cave development by quantifying dissolution rates at the modern mixing zone.

3 - Paleo Mixing Zones: Evaluate vertical changes in lithology that could result in preferential horizons for cave development at paleo sea-levels.

Site Location

Fig. 1

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: 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.

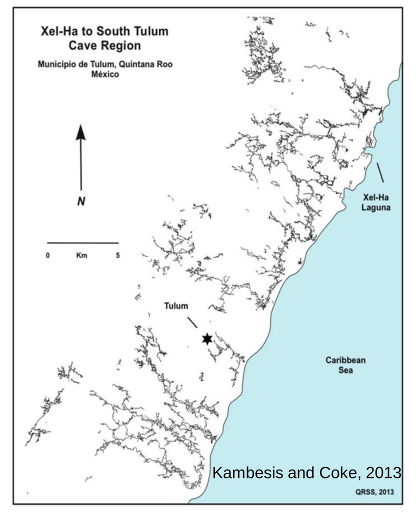


Fig. 2

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). Over 1,500 km of dry and 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. Exploration continues in both dry and submerged cave systems.

Vadose Zone

Fig. 3: Caves in the shallow subsurface exhibit thin ceilings and frequent collapsed entrances. Significant passages are found above the mixing zone of any past sea-level.

- Yucatan soils, while thin, are rich in organics and it is likely that CO_2 enrichment contributes to void formation through meteoric infiltration.
- Variables such as the amount of organic material and soil, climate over geologic time, and changes in groundwater recharge and ground-water levels can account for different depths of dissolution and periods of carbonate precipitation and solution observed in the unsaturated zone of many aquifer systems (Wood, 1985).
- Cave location does not necessarily correspond with the modern position of the mixing zone. Conduits formed in the vadose zone would provide pre-existing pathways for water flow during sea-level rise, and could later be enlarged through mixing dissolution.

Modern Mixing Zone

Fig. 4: Caves near the modern water table contain maze-like passage morphology with many speleothems, indicative of deposition during sea level lows.

- In a low-gradient system, small changes in sea level result in significant migration of the mixing zone, leading to complex overprinting of periods of dissolution and deposition over time.
- From conditions observed at a prominent inlet, Caleta Xel Ha, Hanshaw and Back (1980) estimated that mixing dissolution may result in 3m wide conduits in approximately 10,000 years. Sea level stands of that minimal duration should exhibit corresponding horizons of high permeability.
- While it is reasonable to state that freshwater-saltwater mixing drives speleogenetic processes within a coastal karst system, the end result of this chemical interaction also depends on the particular characteristics of a hydrogeologic setting, including flow dynamics and other sources of chemical reactivity within the system (Fratesi, 2013).

Paleo Mixing Zones

Fig. 5: Caves below the modern water table generally consist of large collapsed rooms with few or no speleothems, and are often accessible only though small connecting passages.

- Chappell and Shackleton (1986) determined that the sea level oscillated near 50 m below modern msl from 35,000-120,000 ybp. This suggests that considerable secondary cavern porosity and permeability could have developed at this depth during the late Pleistocene period of stasis (Marin, 2001).
- A number of sites are known to exist at depths at or below 50 m, notably the Pit and the Blue Abyss, both within the Dos Ojos system. Deep sites are only accessible by technical diving, and consequently little is known about them.
- Local divers report that possible cave entrances are found off-shore between -80 and -100m. These were likely discharge points at a former sea level and could still influence modern groundwater circulation.

Methods

We will test the current conceptual model by simulating conduit development in a hypothetical cross-section using mixing zone depths and water table elevations reconstructed from sea level curves and recharge rates from paleoclimate records.

1- Vadose zone: The role of soil CO_2 will be evaluated through long term sampling at selected sites. Caves at the highest elevations relative to past sea levels will be identified by LIDAR-based DEM paired with survey data of cave ceiling heights. Sites at the highest elevations, and therefore least likely to be influenced by mixing-zone processes, will be monitored for soil CO_2 production for 1 year.

2- Modern mixing zone: Geochemical (i.e., temperature, conductivity, TDS, pH) and flow parameters will be collected throughout the mixing zone to delineate flow paths, characterize hydrologic connectivity between tiers, and support geochemical modeling of dissolution rates.

3- Paleo mixing zones: Calculated dissolution rates will be incorporated into a numerical model to predict the depth of conduit development at paleo-sea levels, which will be tested against existing survey data and refined with site-specific lithologic properties.

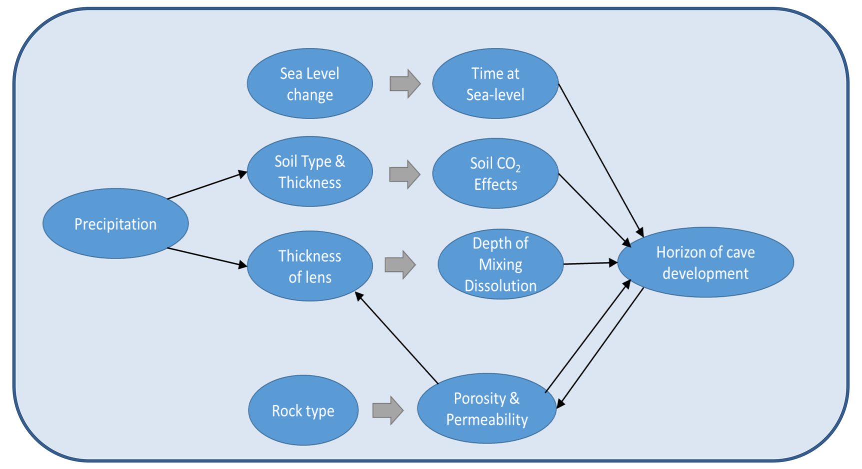
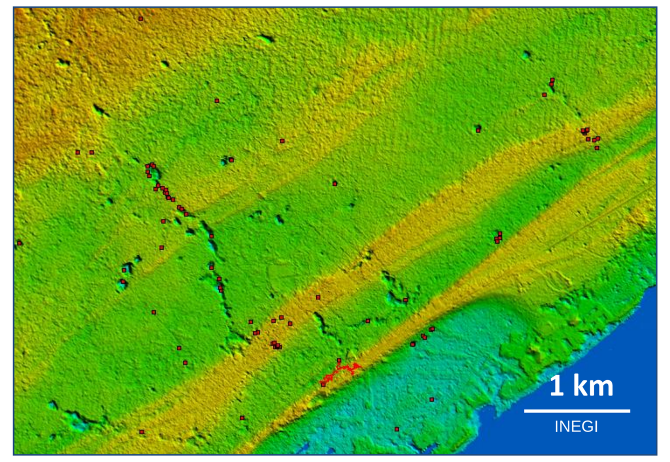


Fig 6: Numerical models will be developed to predict the extent and depth of cave development based on mixing dissolution alone and including the effects of soil CO_2. Modeling will be done using Python with statistical analysis in GIS and R.

Fig 7: A survey of entrances will be conducted to observe differences in entrance density as it correlates with ceiling thickness and distance inland. Dissolution rates will be obtained though the placement of standard tablets, which will be monitored for one year (1 year) in both dry and submerged caves. Statistical analysis of survey data will be used to compare dissolved volumes with model estimates.



Significance

Fig. 8: Sinkhole collapse is a growing concern as urban development expands in the Riviera Maya. This sinkhole opened under the Cancun highway in August of 2015.

- Modeling near-surface conduit development will improve risk assessment for sinkhole collapse, which is especially needed in areas experiencing rapid growth and as development moves inland.
- Understanding the vertical distribution of conduits informs hydrologic modeling to address pressing problems such as over-pumping, saltwater intrusion, and subsurface wastewater disposal.
- The model produced by this study will be transferrable to modern and paleo coastal carbonate systems elsewhere in the world. Understanding the speleogenetic history and hydrologic properties of coastal carbonate aquifers allows for more effective characterization of hydrocarbon reservoir rock that may have developed under similar conditions.

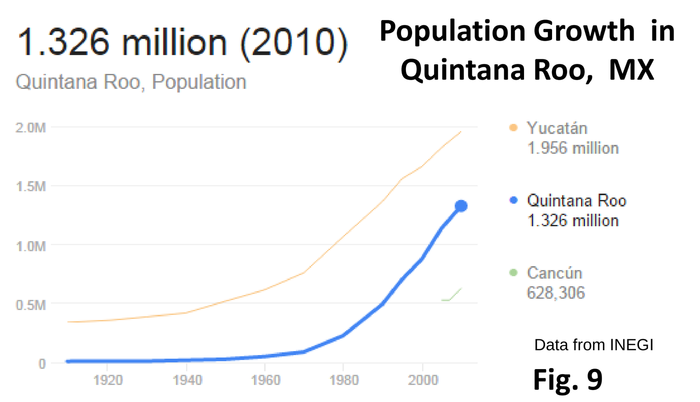


Fig. 9

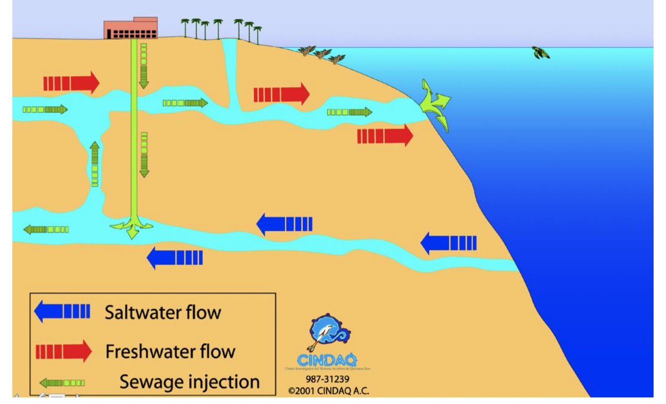
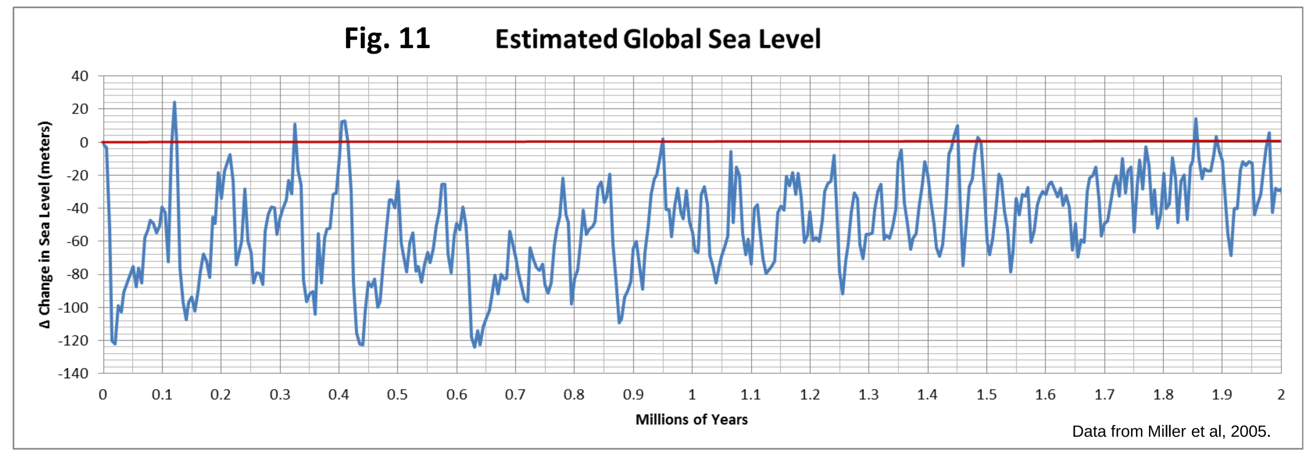


Fig. 10

Fig. 9 and Fig. 10: The rich ecological setting of the Yucatan peninsula has made it a popular tourist destination in the last 30 years and consequently the area has experienced intense population growth, especially along the Caribbean coast. 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.

Anticipated Results

If mixing-zone dissolution is the dominant conduit-forming process, tiers of cave development are expected to correspond to periods when sea level remained stable for significant lengths of time. Each tier will preserve a record of past hydrogeochemical conditions, resulting from overprinting of cave formation processes and secondary deposition during sea-level lows. Correlation between the present mixing zone and active dissolution suggests that the mixing zone is a favorable location for cave formation (Smart et al., 2006); however, many caves exist above the modern water table or any past mixing zone. Gulley et al. (2012) proposed that near-surface caves in Florida are the result of both soil-CO_2 - derived acidity in vadose water and mixing dissolution. Similar geochemical conditions in the Yucatan should form or modify shallow subsurface conduits.



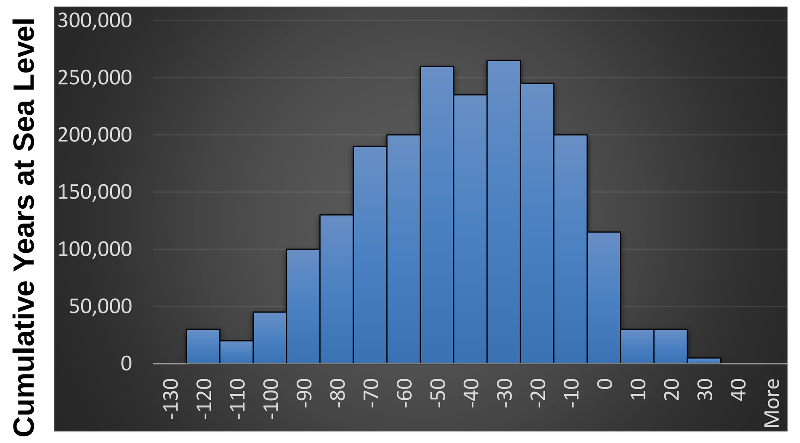


Fig. 12 Depth Below Modern Sea Level (m)

Fig 11 and Fig 12: An examination of past sea level history indicates that for much of the time the platform has been exposed, sea-level was much lower (as much as -120m), yet most cave development is observed near the modern water table (-10 to -20m). Cumulative time spent at a particular sea-level should coincide with conduit horizons.

References

1 Smart, P.L., Beddows, P.A., Coke, J., Doerr, S., Smith, S., Whitaker, F.F., 2006, Cave Development on the Caribbean coast of the Yucatan Peninsula, Quintana Roo, Mexico, GSA Special Paper 404, p. 105-128.

2 Kambesis, P.N., Coke, J.G., 2013, Chapter 16: Overview of the Controls on Eogenetic Cave and Karst Development in Quintana Roo, Mexico, Coastal Karst Landforms, p. 347-373.

3 www.amcs-pubs.org

4 Wood, W.W., 1985, Origin of caves and other solution openings in the unsaturated (vadose) zone of carbonate rocks: A model for CO_2 generation, Geology, v.13, p.822-824.

5 Hanshaw, B.B, Back, W., 1980, Chemical mass-wasting of the northern Yucatan Peninsula by groundwater dissolution, Geology, v.8, p.222-224.

6 Fratesi, B., 2013, Chapter 3: Hydrology and Geochemistry of the Freshwater Lens in Coastal Karst, Coastal Karst Landforms, p. 59- 75.

7 Chappell, J., Shackleton, N.J, 1986, Oxygen isotopes and sea level: Nature, v. 324, p. 137-140.

8 Marin, L.E., Perry, E.C., Essaid,H.I., Steinich, B., 2001, Hydrological investigations and numerical simulation of groundwater flow in the karstic aquifer of northwestern Yucatan, Mexico, Proceedings from the First International Conference on Saltwater Intrusion and Coastal Aquifers— Monitoring, Modeling, and Management.

9 Gulley, J.D., Martin, J.B., Moore, P.J., Murphy, J., 2012, Formation of phreatic caves in an eogenetic karst aquifer by CO2 enrichment at lower water tables and subsequent flooding by sea level rise, Earth Surface Processes and Landforms, DOI: 10.1002/esp.3358.

10 Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., Pekar, S.F., The Phanerozoic Record of Global Sea-Level Change , Science 25 November 2005:, v. 310. no. 5752, p. 1293 – 1298.