OVERVIEW OF THE GEOLOGY AND HYDROLOGY OF COASTAL QUINTANA ROO, MEXICO

Donna & Simon Richards, www.cave-exploration.com

GEOLOGY

The Yucatan Peninsula

The Yucatan Peninsula is a large limestone platform consisting predominantly of calcium carbonate deposited as sediments over many tens of millions of years. The deepest rock strata which have been drilled indicate that the base level was deposited in the Paleozoic epoch, some 250 to 500 million years ago. The shallow surface strata were deposited more recently, with Eocene age rock in the centre (34 to 56 million years ago), Miocene and Pliocene rock surrounding that (1.8 to 23 million years ago), and Pleistocene (1.8 million to 11,500 years ago) and Holocene (last 11,500 years) rock around its perimeter. Most of the Peninsula is low lying, from 5 to 30 meters above sea level, with higher ground (to approximately 60-100 meters) in the Sierrita de Ticul to the west, the oldest surface rock.

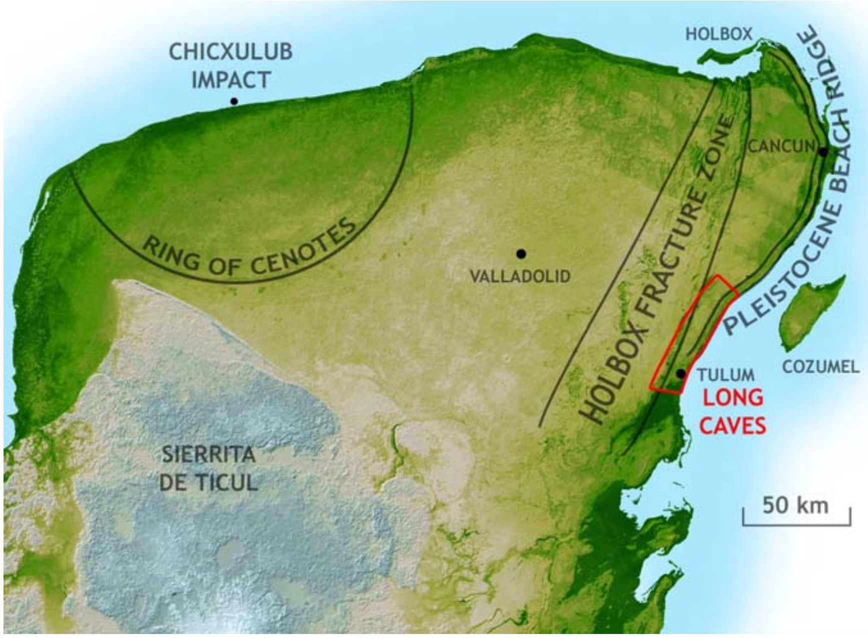


Figure 1: Mexico's Yucatan Peninsula

Principal geographic features include the Chicxulub impact zone, where a 10 km meteor struck some 65 million years ago, now delineated by a "ring of cenotes" at the surface.

On the Caribbean coast, a line of depressions and lagunas known as the Holbox Fracture Zone runs from Holbox in the north.

A few kilometers in from the coast runs an ancient Pleistocene beach ridge, which hosts a number of dry caves and also appears to influence the paths of underwater caves.

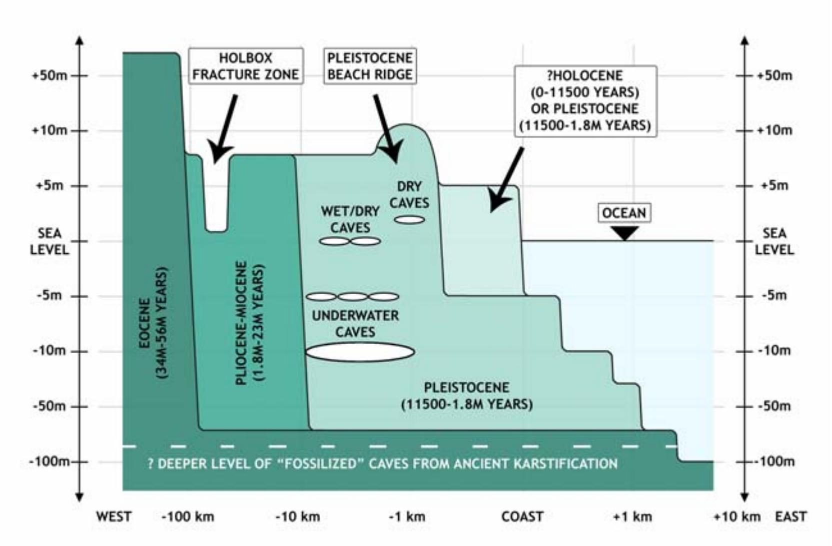
(Image courtesy NASA/JPL)

The state of Quintana Roo lies along the eastern seaboard of the Peninsula and hosts the long underwater caves for which the Peninsula is famous. The location of these caves corresponds to a band approximately 10 km wide of the youngest surface rock, deposited in the last 1.8 million years (Pleistocene and Holocene epochs). Within this band run a series of higher beach ridges typically up to 1 to 2 km from today's coastline, which date from Pleistocene times. Near Puerto Morelos to the north this is a series of closely spaced ridges parallel to the coast, and in the south near Tulum they merge to form a single larger beach ridge. Most of Quintana Roo's known dry caves of significant size are formed under this ridge. The area from ridge to the current coastline is a zone where our knowledge of the underwater caves is hazier - finding diveable cave passage under the ridge is difficult, and most of the underwater caves have not been traced from here through to the ocean.

Rock Stratigraphy

Little is known about the rock layering ("stratigraphy") in the Peninsula, as few research boreholes have been drilled and their cores recovered for analysis. What we do know is that the surface rock is younger closer to the coast, and the rock strata are generally older the deeper one goes. It is also suspected that the area between the Holbox Fracture Zone and the coast moved downwards at some point in time before the Pleistocene, as a result of a process known as "bank margin failure", the collapse of the edge of the platform, and more recent rocks were then deposited on top of the collapsed area. Based on this minimal information, figure 2 shows a conception of the possible subsurface structure.

Figure 2: Possible Rock Stratigraphy



The shallower rocks of coastal Quintana Roo appear to have been deposited as sequences over the last 1.8 million years. The beach ridge may be at the older end of this range, and the rock between that and the ocean may be younger. Most large dry caves are found under the beach ridge, and the long underwater caves lie mostly between the beach ridge and about 10 km inland, roughly corresponding to the limit of the Pleistocene rocks. Further inland lies the Holbox Fracture Zone and then older, higher rocks. Caves are developed at a number of levels, and while most probably have some flow route out to the ocean few of them have been successfully traced.

The Pleistocene was a period with many variations in sea level due to multiple ice ages. As a result the sediments from which the limestone formed were deposited at different times and under different conditions, resulting in a sequence of layers of rock with different characteristics (each layer is known a "bed", and the contact between successive layers is known as a "bedding plane"). Limestone is formed from grains of calcium carbonate aggregated by algae, beach sand, sediments in lagunas and so on, which have been compacted by the weight of overlying rock or sediments. The spaces between the grains ("intergranular pores") may then be partly or completely filled by other material, including finer sediments, which naturally cements the grains together. One particular cementation process which acts on rock close to the surface is known as "calichification". Rainwater may dissolve some calcium carbonate from the grains, and if the climate and other conditions are right, some rainwater may remain close to the surface and later be evaporated. When this happens, the dissolved calcium carbonate from the water is left behind and deposited in the intergranular pores of the rock, eventually filling all of the space between the grains. This makes a denser, harder rock called a "caliche". If all the pores are filled by this natural cement then water will not easily flow through the rock, and it is then described as having a low permeability.

Throughout most of Quintana Roo it is common to see a caliche caprock - a denser, harder bed of rock at the surface which is typically 0.3 to 0.5 meters thick. This caprock was probably formed initially from fine sediments such as mud in lagunas or wetland areas with fairly static water. It may also have been further cemented together by calichification. Generally we can expect the permeability of this layer to be low, but it is now extensively fractured and has other holes through it perhaps from plants or tree roots which provide routes for rainwater to enter the bed below.

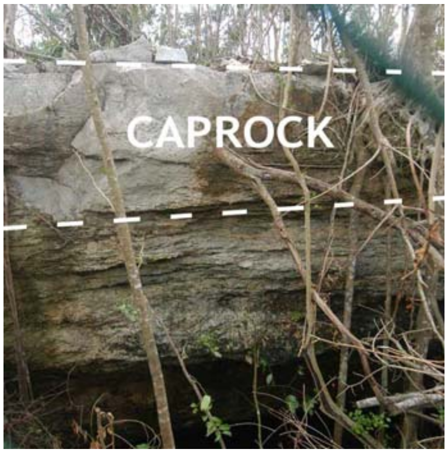


Figure 3: Caprock layer over a cenote

Cores recovered from wells drilled close to the coast have shown similar layers of caliche below the surface, one at about sea level (i.e. 5 to 7 meters below the land surface), and another several meters below that. Insufficient well cores have been obtained to give a very good picture of how extensive these layers may be and how they relate to the beach ridge, but we suggest that they may be significant in determining the water flow routes and where caves form. Where the caliche layers are intact, water may flow along their surfaces, with downward infiltration into the deeper aquifer only where there are fractures and natural holes, and cave formation may therefore be focused in areas determined by the integrity and position of the caprock layers.

Below the surface caprock there are often several thicker limestone beds which can be identified, from a few meters thick to perhaps 20 meters or more. There is some variation between them, but generally they consist of fairly large calcium carbonate grains, with relatively little cementing between them, and therefore high permeability. In some places we see large shells and coral included in the rock.

HYDROLOGY

The groundwater chemistry and groundwater flow is known as the hydrology. Because caves are formed by dissolution of limestone by water flowing through them, understanding the hydrology is a key part of understanding the processes by which caves formed. However the presence of caves will also affect the hydrology.

Coastal Hydrology Prior to Cave Formation

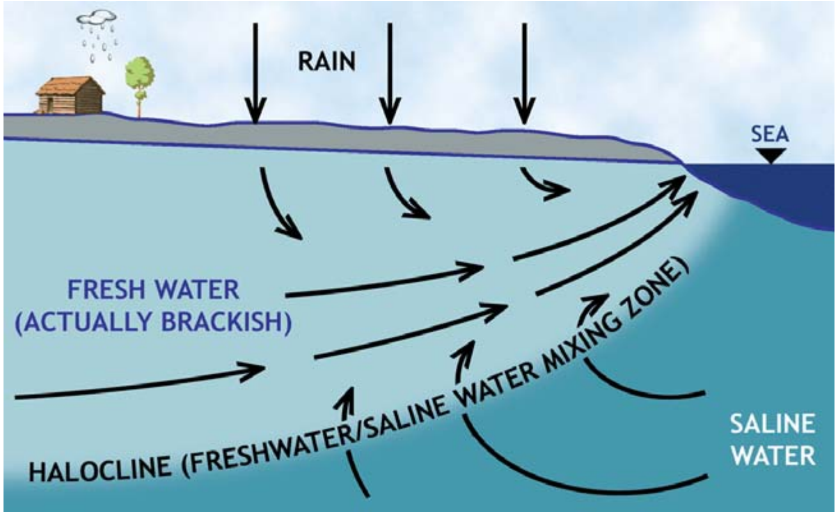


Figure 4: Hydrology prior to cave formation

In a coastal system, the groundwater consists of a freshwater "lens" floating on top of saline water. Freshwater flows out to the sea as a distributed diffuse flow, perhaps through the intergranular pores in the rock. There is some mixing between the freshwater and the saline water, so that the freshwater becomes brackish.

Because some saline water is being mixed into the freshwater and then discharged with it to the ocean, there must be a compensating saline inflow below.

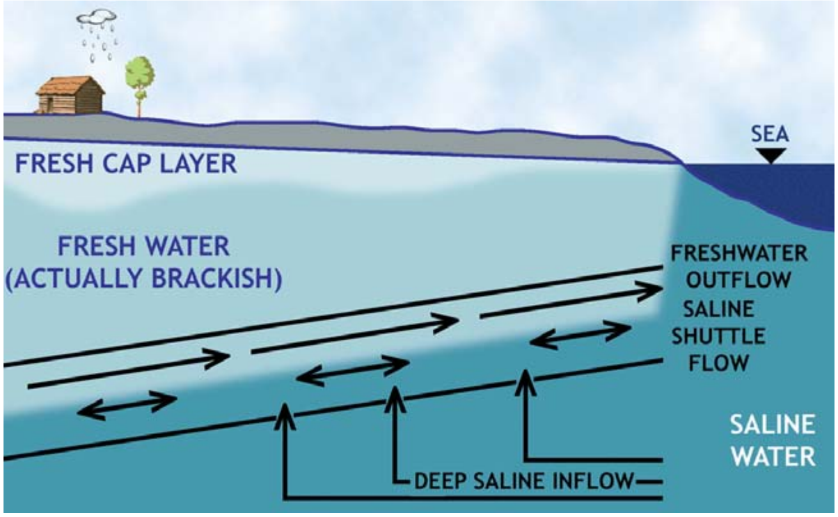
Prior to cave formation (figure 4), all flows are assumed to have been evenly distributed between many different routes (through the intergranular pores in the rocks, through some bedding planes, or through fractures in the rocks formed by expansion, contraction and settlement of the Peninsula). This results in a "lens" of freshwater floating on top of the saline water (because the fresh rainwater is less dense than the saline marine water). As the freshwater flows through the rock, there is some mixing at the interface with the saline water (the "fresh-saline mixing zone" or "halocline"), making the freshwater slightly brackish. The freshwater is discharged into the ocean along with the saline water which has become mixed in with it, and so for the system to remain in balance there must be a compensating inland flow of saline water.

Karstification

The formation of the caves changes the hydrology. The flow of water dissolves rock along its route, more rapidly where there was the most flow, in turn increasing flow in that route and therefore increasing the dissolution rate along that route. As a result, the routes which are the largest grow most quickly. This positive feedback effect causes some flow routes to grow to the point where they become sufficiently large to become classified as caves (i.e. large enough for a person to enter), with most of the water flow being focused into them. The process is known as karstification, and variants of it are responsible for all of the karst landforms we see (caves, sinkholes and so on).

Present-Day Quintana Roo Hydrology

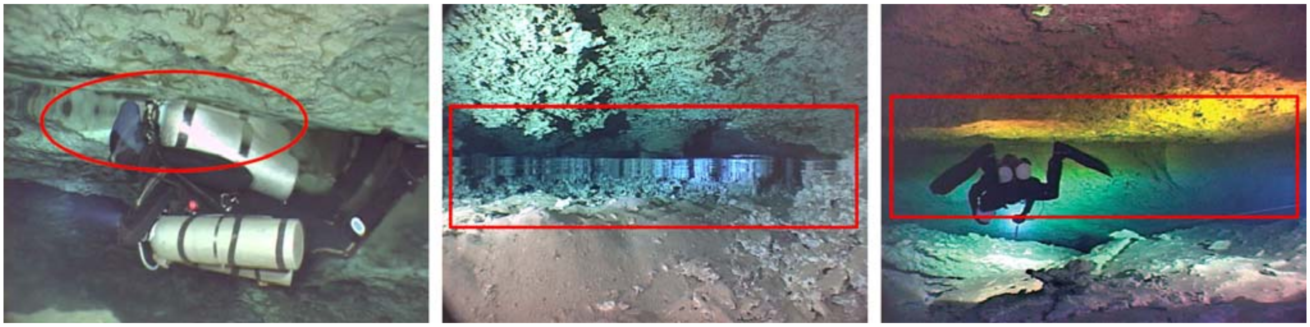
Studies by Patricia A. Beddows, PhD at McMaster University in Canada, a hydrologist, caver and cave diver who has done research in Quintana Roo, suggest that most of the water flows through the caves before reaching the coast. Some of these caves contain only freshwater, but many of them also have saline water below the freshwater, and a visible halocline. There is still mixing between freshwater and saline water, and as a result the freshwater becomes brackish.



<u>*Figure 5: Hydrology after cave formation*</u>

Studies by Dr Patricia A. Beddows have shown that the vast majority of the freshwater is discharged via the cave systems and coastal springs. As a result the freshwater lens is no longer curved but is much flatter and follows the level of the caves. There is still a deep inflow of saline water, possibly through a system of older deeper caves, and additionally there is a "shuttle" flow of seawater into and out of the caves as sea level rises and falls with the tide and other factors, extending several kilometers inland from the coast.

Beddows has also documented a saline "shuttle" flow from the sea via the cave passages: when sea level rises and falls, as a result of the tidal cycle, changes in barometric pressure and so on, there is a flow of saline water in and then out through the cave passages. Additionally, floating on top of the freshwater layer is a so-called "fresh cap layer" which is normally much less saline and may be tannic, corresponding to groundwater which has yet to join the flow system. It can be seen in domes in underwater caves, and the water in some cenotes consists of this fresh cap layer rather than the water flowing in the cave systems (figures 5 and 6).



<u>*Figure 6*</u>*: Video frame grabs from caves in the region showing contrasting water layers. (left) Diver in the halocline - the diver's head and tanks are distorted due to the difference in density between freshwater and saline water diffracting light rays. (center) Light diffraction and waves on the halocline. (right) Tannic fresh cap layer floats on top of the freshwater layer in a dome (color saturation boosted to show difference).*

ENVIRONMENTAL SIGNIFICANCE

The relatively rapid flow of water through the caves (up to several kilometers per day) may transport environmental contaminants over large distances without any natural filtration and before natural processes have had time to break them down, and the flow directions are not just from inland to coast as one might intuitively expect.

Effluent Disposal

Current practice is to obtain freshwater from wells about 10 km inland, and to inject effluents into the deep saline water close to the coast, where the hotels and most of the population are. This is based on the assumption that the freshwater is flowing from inland to coast, and the saline water is largely static, but there are two problems with these assumptions.

Figure 7: A tourist cenote near Tulum. Beddows' work has shown that such cenotes contain combinations of water originating from the saline water zone, the freshwater layer, and the fresh cap layer, and therefore are at risk from contamination transported in any of these layers.

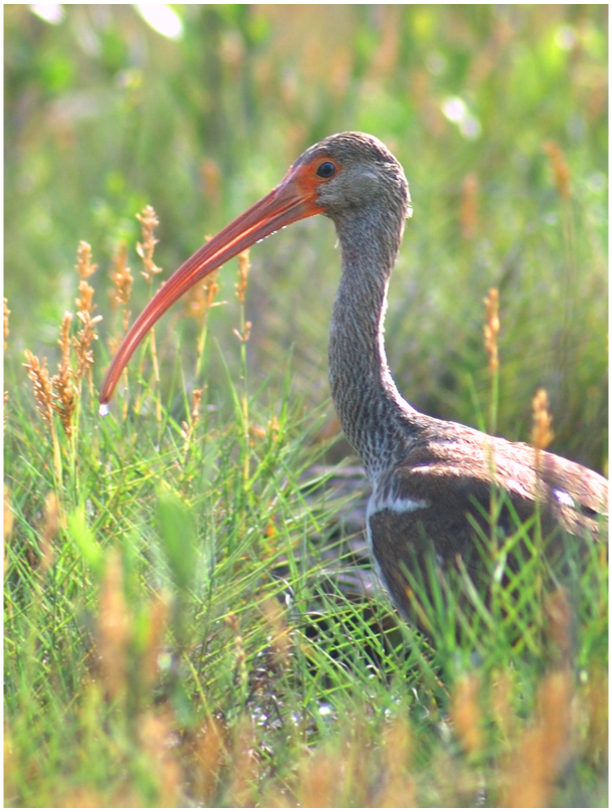


Figure 8: One of several coastal wetland areas near Tulum. These are migratory feeding zones and breeding grounds for a wide range of birds. The water in them may be part of the fresh cap layer and its flow may be determined by geological factors such as calichified caprock layers, but insufficient is known to assess the risk posed by environmental contamination.

The first problem is that effluent tends to be closer to the density of freshwater than saline water, so it will rise up to the fresh-saline mixing zone or into the freshwater (recent studies in the Florida Keys have shown that effluent can resurface in a matter of hours or days). The coastal area where effluents are injected is highly active hydrologically, with the saline shuttle flow inland and out connecting all of the tourist cenotes and beaches, and the freshwater flow out onto the beaches and reefs, so buoyant effluent could be transported to all of these places.

The second problem is that even if the effluent were mixed with a hypersaline water to keep it dense enough to stay in the saline water zone, Beddows' work shows this water may flow long distances inland quite rapidly with the shuttle water, and still eventually rise to be mixed with the flowing freshwater. Contamination of the saline water system could therefore result in contamination of the freshwater supplies, the cenotes, the tourist beaches and the reefs, all of which underpin Quintana Roo's economy.

Fresh Cap Layer

Contamination of the fresh cap layer is also potentially troubling, because it probably supports the wildlife in many of the wetland areas, but little is known about the distribution or flow of water in this layer.

Removal of Coastal Barrier

Another concern is the potential loss of the freshwater and fresh cap layers due to construction of marinas and "waterfront" accommodation, which involves cutting trenches inland from the coast, removing the shallow rock strata and permitting easy water flow from inland to ocean.

In 2005 Hurricane Wilma removed sand from the beaches between Cancun and Tulum, exposing temporary springs through fractures in the caprock. This suggests that there may be a shallow flow system between the beach ridge and the ocean which is confined by the caprock layer where it is intact. "Waterfront" developments and construction of marinas could breach this caprock layer and open up flow systems, causing the loss of the fresh water layer.

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Figure 9: (top) Temporary coastal spring through caprock fracture on beach in Playa del Carmen, after Hurricane Wilma. (bottom) "Waterfront development" in Puerto Aventuras.