AN INTRODUCTION TO THE YUCATAN PENINSULA HYDROGEOLOGY:

A world class example of a coastal carbonate density stratified aquifer

Patricia A. Beddows

The Yucatán Peninsula

The carbonate rocks of the Yucatan Platform are highly porous and started to be deposited 65 million years ago. Many successive thick layers were deposited so that the total thickness today is between 1 and 2 km for most of the Yucatan Peninsula, which is the part of the Yucatan Platform that is above sea level. The near surface rocks have not been affected to any great extent by tectonic activity, compaction due to burial by layers of other rocks or sediment on top of them, or large scale chemical processes called diagenesis that alter the chemical composition of the rock (although dolomitization where the mineral dolomite is formed has been recognized). Consequently, the carbonate rock that you can see on the land surface and in the cenotes and caves is ‘diagenetically immature’ retaining for the most part the original high porosity. Many excellent fossils may be seen and the rock layers remain nearly horizontally bedded.

Soluble Rock + Water = Karst

An aquifer is any water bearing rock. A rock may be highly porous, but these pores must be open to each other and interconnected for water to flow through the rock. When water flow through a soluble rocks (limestone, dolomite, marble, some sandstones, etc) over geological time periods, then the water will eventually find preferential pathways. These pathways will increase in size and improve in hydrological function through ongoing dissolution of the rock, to form what we call caves. The preferential pathways may be bedding planes, which in the Yucatán are still lying nearly horizontal in their original depositional angle. Pathways may also be more vertical such as fractures, fissures, tree root holes, etc.

Where, how, and why dissolution occurs in karst aquifers is an active area of scientific investigation and processes that affect continental karst such as in Texas (US), Kentucky (US), British Columbia (CD), or the Dordogne (FR) may differ significantly in some respects to the case of the Yucatán Peninsula. These continental locations mentioned are invariably uplifted, tilted, and/or chemically altered, whereas the Yucatán Peninsula is not. Importantly, the Yucatán is also a coastal system, affected by oceanic forcing and experiencing mixing between fresh and sea-water. Despite being categorically different than many well-known karst regions of the world, the Yucatán is not unique and many similar but smaller coastal carbonate aquifers exist. They occur most notably on tropical and neo tropical islands such as in the Caribbean and the Mediterranean, they occur on peninsulas and islands of Southeast Asia, some coastal regions of Australia, and many other locations.

What is common among all karst aquifers is that the water drainage occurs underground through an organised system of specific passages where small flows feed large flows, and that grows in form and efficiency with ongoing dissolution of the rock. It is similar to surface river systems but karst systems are often overlooked or poorly understood because they occur in the three dimensional space below the ground surface. The Yucatan aquifer is often likened to a sponge, but this analogy is inappropriate to describe the veritable underground river system that transports the water.

Karst aquifers are indeed predictable. The water will develop pathways, and the water will flow from a point and to a point. Springs are discharge points of distinct flow paths that may be water filled passages centimetres to metres (inches to feet) in diameter. All the features that we call karst features are intrinsic parts of a complete flow system. The **rock** is the frame or matrix, the **caves** are the pipes, the **cenotes** are weak points in the ceiling that have opened up as windows into the system, and the **coastal springs** are the final destination of all fresh water in the system. Among karst aquifers, the Yucatán peninsula is very well hydrologically connected indeed as demonstrated by the number of large discharge springs and caletas along the coast, and the length and distribution of explored hydrologically active cave systems known to provide flow to them. Almost 400 km of submerged passage, often more than 5 m, have already been explored and surveyed along the Caribbean coast of the Yucatan Peninsula alone.
(see: www.caves.org/project/qrss/qrlong.htm). Although the carbonate rock itself may be said to be ‘immature’ because it is not very altered, the Yucatán as a functional hydrological unit is a very mature karst aquifer capable of effectively transporting very large volumes of water.

Where does the fresh water come from?

Rain infiltrates through the porous surface rock and down through fissures where it forms a distinct layer of cooler less dense fresh water that sits on top of the intruding saline water. This is the fresh water 'lens', and it is generally thicker inland, becoming progressively thinner as you approach the coast. It is more than 30 m thick 30 km inland, approximately 30 m thick at Cenote Angelita at 11.7 km inland, and between 10 and 20 meters in most of the cenotes and caves you may visit less than 10 km from the coast.

Precipitation on the Caribbean coast of the Yucatán is reported to be approximately 1.5 metres per year. A large proportion of the total reaches the aquifer although some is evaporated and/or used by the forests and vegetation. You can see this if you are in a dry section of a cenote or a cave as drips in the ceiling and water rivulets will begin to flow within minutes of the rain starting.

Flowing Fresh Water

The fresh water flows are driven through the network system by many forces and processes. The greatest force is gravity that drives water downwards towards sea level. The surface level of the fresh water lens fluctuates in response to ocean tides, rainfall, offshore winds, barometric pressure, and others forces yet to be investigated. The higher the water level in the aquifer relative to sea level, the greater the mass of water affected by gravity, and therefore the faster the water will flow in the conduits. It is the therefore the dynamic balance between the surface of the fresh water lens and the position of sea level that controls in great part how much water flows out of the aquifer via the coastal springs, and how fast.

Seasonal variations of absolute water level in the cenotes are significant with observations by local cave divers indicating that the water table may vary as much as one meter annually. Semidiurnal fluctuations driven principally by the tides is more on the order of 5 cm if you are 3 km from the coast. You will have to be very perceptive to notice these twice a day changes in a cenote however even the smallest change in water level represents the displacement of very large volumes of fresh water in the system. A 1 cm change in water level over the area between Playa del Carmen and Tulum (~150 km), and 10 km inland, assuming an aquifer porosity of 25%, means that 3 750 000 cubic meters, or almost 1 billion US gallons of water is displaced in the system for that one centimeter. However the fresh water lens is ~ 10 m thick on average in this zone, therefore the potential volume of water displaced by the daily and seasonal aquifer motions is indeed phenomenal.

The water flows through the carbonate rock at a rate of cm's or inches per year. However in the large conduits, the water flows at a rate of kilometres or miles per day. Dye tracing and flow instruments in the many Yucatán cave systems including Nohoch Nah Chich, X-Caret, Ponderosa, Xel Ha, Maya Blue, and others show that water flows, although often nearly imperceptible to the diver, are generally between 0.5 - 2 km per day. If you swim in the Main Entrance cenote of Nohoch Nah Chich one day, you may encounter the very same water two days later as you enjoy a swim in Casa Cenote (aka Tankah and Manatii) on the coast.

The water in the cave conduits is slowly drawn from the rock walls. Only a little bit of water has to flow from each section of cave wall to provide for the conduit flow as the peninsula is very wide with a distance of ~75 km from the middle to the coast. At present very few cenotes in the interior of the peninsula have been explored and infrequently are large diameter open conduits been found in them. Like river systems where many small creeks feed the principal river-ways, we may eventually find that mostly small caves on the order of 10's of cm in diameter exist in the very interior of the peninsula. Alternatively, large cave systems may exist there but these are occurring deeper in the aquifer (more than 100 m depth) and many have been partially or totally collapsed. Although collapse of rocks into a passage may make our exploration difficult, water may still flow around these obstructions. What is certain is that the interior of the peninsula contains a vast volume of fresh water that is slowly drained to the coastal springs via the cave systems and cenotes that you are becoming familiar with.

Hydrological Chracteristics of Sistema Nohoch Nah Chich
Ejido Jacinto Pat, Municipalidad de Solidaridad, Q.R., México

	Rock matrix	Fracture	Cave conduit
% total fresh water in STORAGE	99.6	0.6	2.8
% total fresh water FLOW	0.02	0.2	99.7

(Beddows, 1999)

Where does the saline water come from?

Sea-water naturally intrudes into coastal aquifers regardless of whether they are carbonate soluble rocks or not, and this phenomenon has been well known for more than 100 years. The conventional model to describe the system is called the Dupuit-Ghyben-Herzberg model (called "DGH" hereon) and only recently has the ready access to hydrologically active cave passages been adequate to start assessing how valid this model is to karstified aquifers like the Yucatán Peninsula.

Flowing Saline Water

The underlying saline water is increasingly found upon examination to be very dynamic with somewhat slower flow rates than that of the overlying fresh water. The long standing DGH tells us that as the fresh water flows towards the coast, it will drag the underlying saline water along with it in a process called entrainment. Numerical modelling efforts indicate that the entrainment should extend to several tens of meters of depth below the halocline. However recent observations to the effectiveness of entrainment using dye tracing and instruments in various systems including Ponderosa, Dos Ojos, Naranjal (Maya Blue) indicate that the direction of saline flow may change seasonally within the caves systems, and be controlled by the ocean cycles. The saline water flows on the order of 1 km per day in both inland and coastal directions. These important flow reversals mean that any contamination in the saline water may be well distributed over long distances and also inland!

It is known that the water discharging from coastal springs varies between one/third to two/thirds saline water depending on the specific spring, sea level, tidal cycle, and the season. Even if entrainment is not a significant driving process, it is still certain that there is a significant amount of saline water taken up into the fresh water lens through molecular diffusion and mechanical mixing between the two water masses, and that this saline water is still ejected back out at the coast. To compensate for this loss of saline water in the system, ocean water must circulate into the aquifer to replenish the volumes of saline water that are lost through the coastal springs. The DGH model tells that an inland flow of saline water is occurring at depth. The inland flow of saline water is numerically modelled to occur possibly at depths of 10's to over 100 metres deep within the aquifer. Given the recent discovery about the dynamic nature of the saline water only a limited distance below the base of the halocline interface, we must now question this model, and test to see where, how and when the saline water is flowing into our coastal Yucatán system.

What is the Halocline?

An interface forms between two liquids of different densities. The interface between your olive oil and balsamic vinegar for your salad dressing is unwanted so you quickly try and destroy it by shaking the bottle. In the Yucatán aquifer, the 'bottle' never get shaken to a great extent so an interface exists between the fresh and saline waters even though the contrast in density is much less than that between oil and vinegar. The interface is the HALOCLINE. 'Halos' refers to the halogene group of elements of which the most common member is chloride (if you remember your periodic table, it is the second last from the right. Chloride is also the major constituent in sea salt. 'Cline' refers to a gradient or a slope. Therefore 'halocline' is where there is a strong gradient or change in salt concentration.

It is a wonderful experience being able to see and play with the halocline in some cenotes and caves! You can see it with your eyes because some of the beams from your light are refracted, or bounced off the halocline surface. This is also why the halocline may look different from above and below as the angle of reflection is different depending whether you are looking from the fresh or saline water into the other.

Mixing Across the Halocline

The halocline is also a mixing zone where some of the saline water is mixed into the fresh water lens. As mentioned earlier, the water flowing out of the coastal springs is brackish, that is, it contains a significant amount of salt water. The addition of salt into the fresh water lens naturally occurs over the whole of the halocline surface through several processes. Molecular diffusion of ions slowly transfers ions from the saline to the fresh side of the halocline. Mechanical mixing may occur where water passes around and between obstructions in the flow path such as breakdown boulders and stalagmites and stalactites. Pumping actions on the aquifer such as from oceanic loading may also contribute to the mixing. The daily displacement of the halocline due to tides has been observed to be ~ 4 cm, 1.6 km from the coast at one site, and vertical displacement approaching half a meter at another site 1.8 km inland. These are not huge displacements, but very large volumes of water are implicated if you recall the earlier calculations of the volumes of water involved in displacing the water surface by 1 cm. Although the displacement does not destroy the halocline, a certain amount of mixing is associated with these movements. That is why the fresh water lens is increasingly saltier as you approach the coast where tidal pumping is strongest, and why the water is much fresher inland, say in Cenote Car Wash.

Hurricanes and tropical storms are major perturbation events every year for the aquifer. Water levels have been observed to rise dramatically more than 1 m at many sites. The aquifer is disturbed not only by the large volumes of rain entering the system but also the build up of pressure from the associated winds, and the major changes in barometric pressure. In response, the halocline has been observed to loose it distinct structure and become mixed through a thicker depth of water. Amazingly though, within 5 tidal cycles (less than 3 days) after the event, the halocline regains most of its distinguishing characteristics such as depth position and thickness.

The most likely halocline you will see in a cenote is at Cenote Eden. Here the thickness is measured to be less than one meter for the salt content of the water to change from the fresh water lens to the near ocean salnity of the underlying saline water. Haloclines are not necessarily so sharp, and in fact may often be very thick spanning many meters. If you are very observant and use your light as a refraction tool, you will even be able to see the multiple layers within the halocline. Usually the first and last cline are the sharpest and most visible. A good place to observe a complex and thick halocline is B tunnel off of Maya Blue Cenote.

The Corrosive Halocline and Past Sea Levels

Both the fresh and saline water have spent much time in contact with the host rock of the aquifer and so are generally considered to be at or near saturation with dissolved rock minerals. However, the dissolutional potential is not a linear function. This means that if you mix two saturated solutions in equal parts, the resulting mixture will be undersaturated and capable of dissolving even more rock, thus enlarging the cave. This effect is called mixing corrosion and it is a horizontal process in the aquifer occurring along the halocline. Sea level is the ultimate control on where mixing corrosion will occur as it controls the dynamic balance between the depth of the halocline and the thickness of the fresh water lens.

We know that the caves and cenotes we enjoy formed for the most part during a previous geological time. In between times (~ 10 000 years ago), sea levels were much lower than present. The caves were dry during this period allowing for the deposition of beautiful stalagmites, stalactites and flowstones as these formations can only form in air filled cave environments. Many archaeological remains and artefacts are found below water that could only be in their present position if the caves were dry for an extended period of time.

It is in fact possible that the Yucatan cave systems formed more than one period of low sea levels ago, and have undergone more than one wet/dry cycle. The actual age of the caves remains to be determined through careful analysis of the cave morphology and dating by chemical analysis of select cave deposits. The water filled cave systems and cenotes therefore are re-flooded as sea level is now risen again to a high level. However the increasing length of dry cave being discovered above the current water table indicates that substantial karstification occurred when sea levels were even higher still (IF the Yucatan platform has not risen or fallen in absolute position due to tectonic activity). In fact, sea levels 6 meters higher than present occurred ~ 120 000 years ago, providing a provisional age date for these higher level, now dry caves.

One implication of the cave systems having formed during a previous geological period where sea levels where different than present, is that we do not know if the current hydrological system is in balance with the physical structure and layout of the caves. It is possible that current hydrology is out of balance, and therefore the ongoing dissolution particularly through mixing corrosion at the halocline is actively changing the regional hydrology to approach a new equilibrium in balance with current sea level. This potentiality is being tested through extensive chemical analysis and biogeochemical experiments (See entry by Smith, this volume).

We must not also forget that the Yucatán limestone rocks remain near their horizontal deposition angle. It is therefore a difficult task to unravel how much of the horizontal cave development is due to water flowing preferentially along a bedding plane creating near horizontal cave passages, and how much horizontal cave development may be attributed to mixing corrosion along the also horizontal flat surface of the halocline.

Stalagmites and Stalactites – the Key to the Past

Cave deposits are wonderful repositories of geological information. We may determine how old they are, and therefore how long ago the

cave was air filled, but also derive information on past rainfall rates and sea levels.

It is impossible to say how old a cave deposit is from its length, or provide an average of how fast they grow. Deposition of cave deposits only grow when there is dripping water into an air filled cave (there are a few very rare exceptional types, but these have not been identified in the underwater Yucatan caves). Because drip rates can be highly variable, cave deposits often grow in spurts and may stop growing when conditions are too dry. Consequently, a deposit that is 80 000 years old at its base and 10 000 years old at it top, may in fact only contain 10 000 years worth of growth record and not 70 000, as the drip that fed it simply was not active for 60 000 years. Therefore two deposits beside each other may tell completely different stories over different time period depending completely on how consistently active the drips were that made the formations. As a very crude rule of thumb, cave deposits may grow cm's per 1000 years. Because of their beauty and the fact that they are indeed irreplaceable, they should not be disturbed and touching should be avoided.

Contamination Risks

Karst aquifers are considered particularly sensitive to contamination for several reasons. Most contamination sources will impact more immediately on the saturated aquifer rock and not on cave passages, independently of whether the contamination is from above (cars, cess pits, fertilizers, garbage dumps, etc), or from below (sewage pumped into disposal wells). This means that the contaminant will migrate through the rock system on the order of cm's per year, until the moment that water then flows into the conduit system. From then onwards, the water will flow km's per day. This important delay means that weeks or years may pass before the contaminant becomes evident in the cave systems, the cenotes, and the coastal springs. Also, the contamination may be transported several kilometres from the actual source. These spatial and temporal factors make identifying the source extremely difficult.

Once the contamination problem is evident, it is also very difficult to remediate the problem as very large volumes of the contaminant may have built up in the rock storage over the years. This will slowly leach out the rock, impacting the cave system, subterranean ecosystem, and the coastal reefs onto which the groundwater will discharge, potentially for years to come. Clearly prevention must be the focus of waste management decisions, and not remediation.

Two contamination issues are of particular concern on the Caribbean Yucatán at the moment. First, these are uncontrolled leachates from the garbage dumps that are often situated in old quarries often with less than one meter of dry rock between the garbage and the aquifer. Second, all aspect of sewage disposal will pose serious challenges to the ongoing tourism driven development of the region. For greater discussion of these threats, please see the entry by Beddows, this volume.

While at this time, much of the jungle aquifer remains unaffected and pure, continued scientific study and an increased environmental awareness are critical to the understanding, protection and preservation of the world's most critical natural resource, the water.