WIREs WATER

Article type: **Focus Article**

The Proyecto Costa Escondida: Recent interdisciplinary research in search of freshwater along the North Coast of Quintana Roo, Mexico

Authors:

First author Patricia A. Beddows, Northwestern University	
Second author Jeffrey B. Glover*, Georgia State University	jglover@gsu.edu
Third author Dominique Rissolo, University of California, San Diego	
Third author Alice M. Carter, Northwestern University	
Third author Beverly Goodman Tchernov, University of Haifa	
Sixth author Roy Jaijel, University of Haifa	
Seventh author Derek M. Smith, University of Washington	

Abstract

Access to potable water has always been a major concern for human settlement, and this is particularly acute in coastal areas where freshwater can be compromised by saline marine waters. The northeast portion of Mexico's Yucatan Peninsula has a massive freshwater aquifer that today supports the international tourist destinations of Cancun and the Riviera Maya. However, access to this aquifer in Precolumbian times was restricted to natural features, such as *cenotes* (limestone sinkholes), *aguadas* (freshwater ponds), and coastal springs, or cultural features like wells; the viability of which are directly linked to sea level, which has risen over 2 m in the past 3000 years. In addition, ancient Maya inhabitants of the Yucatan collected rainwater in reservoirs, or smaller-scale cisterns, called *chultunes*, or in ceramic pots. At the coastal site of Vista Alegre, located on the north coast of the Peninsula, there is limited evidence of potable water collection strategies, which has led members of the Proyecto Costa Escondida to critically examine how the freshwater access at the site changed over the past three millennia. To do this, the interdisciplinary research team is conducting 1) a physico-chemical characterization of accessible surface and groundwater using a calibrated multi-parameter probe, 2) a multi-proxy study (i.e.,

micropaleontology, oxygen isotopic analysis) from 12 manual push cores taken in the waters surrounding Vista Alegre, and 3) an archaeological investigation. We hope our project serves as a model for future projects that strive to understand the complex and dynamic relationships between past peoples and their coastlines.

Introduction

The coastline of the Maya world extends from modern day Honduras up and around the Yucatan Peninsula to the coast of the Mexican state of Tabasco. The coastline is dotted with settlements linked in Precolumbian times through long-distance trade routes, and extends to islands such as Cozumel and Isla Mujeres[1,2] (**Figure 1A**). The majority of this coastline is a karst geology, where freshwater flows through underground river systems, and is only accessible on the surface through sinkholes, or at coastal springs[3,4]. While the Caribbean coastline and the coastline in Tabasco have high precipitation rates, the northern coast is characterized by < 750 mm/year precipitation, and extensive hypersaline lagoons and mangroves. To date, the northern coastline of Quintana Roo has received cursory attention from archaeologists. It was this lacuna in knowledge plus our previous research in the area[3-9] that led us to form the Proyecto Costa Escondida (PCE), which is investigating the dynamic relationship between the Maya and their coastal landscape over the past 3000 years.

In particular, our research has focused on the ancient Maya port site of Vista Alegre (**Figure 1B**). From the inception of our project, we recognized that access to freshwater was a major logistical challenge for us, and we knew from local inhabitants that the neighbouring modern port site of Chiquilá was abandoned about 60 years ago for a period of time due to lack of freshwater (Don Vio, personal communication). We began to wonder how the past inhabitants of Vista Alegre would have dealt with this issue. From our previous work in the area, we were familiar with larger springs along the north and east coasts, some discharging over 1m^3/s of water[5], and we had all read the historical accounts of the conquistador Montejo and his men watering their horses off-shore at one of these springs[10], locally referred to as *ojos de agua*, but there were none near Vista Alegre. The closest springs to Vista Alegre were small ones about 6.5 km to the west. There was a larger one that is a popular tourist destination, but it is 14.5 km to the west. None of them are close enough to Vista Alegre to have been viable daily sources for the site's water needs. We continued our exploration for a potable water source to the mainland south of the site. We found four small karst depressions approximately 2.8 km south of the site's main habitation area, but their small size and distance from the site made us doubtful that they would have served as the principal water source for Vista Alegre. Another tactic used by the ancient Maya to store freshwater was the construction of *chultunes*, or cisterns[11]. While three of these have been recorded at Vista Alegre, they certainly would not have held enough water to supply the island's inhabitants and visiting traders with water during the dry season. At Vista Alegre, therefore, we believe that a closer, permanent water source must exist, or previously existed during lower sea levels. In this paper we discuss our efforts to understand how past inhabitants managed their limited freshwater resources.

The first section of this paper describes the geology and hydrogeology of the Caribbean and northeast coast of the Yucatan Peninsula and discusses how it has changed over the past three millennia in order to understand the physical constraints placed on freshwater access for coastal Maya settlements. The second section focuses on what is known about the strategies used by coastal inhabitants in the Maya area to deal with freshwater access issues. What we find is that even when water sources (e.g. wells, cenotes) are identified during archaeological investigations, they are more often than not unsampled, untested, and the water quality (based on physical, chemical, and biological properties) unassessed. Moreover, archaeologists do not always take into consideration seasonal and longer-term variability with respect to potability. These are issues that our project is directly addressing. The third section of the paper introduces the interdisciplinary methodology and the initial results of the PCE's attempts to elucidate water access and management at Vista Alegre using sediment cores, water chemistry, regional geology, and geoarchaeology in addition to traditional archaeology. By critically assessing freshwater access, we hope our project serves as a model for future projects that strive to understand the complex and dynamic relationships between past peoples and their coastlines.

[The Yucatan Peninsula – Geology and Hydrogeology]

The Yucatan Peninsula is the exposed portion of the extensive carbonate Yucatan Platform that spans 800 km north-south, and 600 km from the Caribbean Basin across to the northwest into the Gulf of Mexico. Along the Caribbean coastline, the water drops to thousands of meters of ocean depth within tens of kilometers of the modern shoreline. Strong northward currents limit coastal sedimentation, leaving a rocky coastline interspersed with sandy bays protected by the extensive Mesoamerican Barrier Reef System (MBRS). In contrast on the north coast lies the shallow Campeche Bank with water depth <100 m, even out to ~300 km offshore. Transported sediment accumulates on this bank, and the vast area is a modern "carbonate factory" where thick accumulations of $CaCO_3$ rich muds and oozes are precipitated. Rocky exposures on this northern coastline are quite scarce. Barrier island complexes formed with western openings begin at Cabo Catoche north of modern-day Cancun, and occur along the northern coastline due to the westward flow arm of the strong currents that move from the Caribbean Basin and bend westward around Cabo Catoche.

Rainfall on the young, porous, and permeable limestones of the Yucatan quickly infiltrates downwards, leaving no flowing surface water throughout the northern 300 km of the Peninsula. Even though rainfall ranges from 1500 mm in the northeast Caribbean coast (near Cancun and Puerto Morelos) down to an arid ~400 mm in the northwest near Progreso, the vegetation throughout the Peninsula shows evidence of adaptation to dry conditions due to the effective infiltration. This infiltrating meteoric water forms a distinct lens of fresh groundwater, literally floating on top of higher density infiltrating marine water that comes in from the coastlines. Where the fresh and saline water meet, the chemical effect of mixing corrosion effectively dissolves flowpaths to form underground rivers, or caves, measuring between 5 m and 50 m in width[4]. The dissolution of the rock to form these underground rivers is the process of karstification[12]; as with all karst groundwater systems globally, the vast majority (~99%) of the water flows through the cave systems formed by dissolution[13].

The elevation of the freshwater surface – the water table – is principally controlled by sea level. During the Pleistocene, sea level has varied from present high levels down to ~120 m below sea level with glacial-interglacial variations. At lower sea levels, the freshwater lens sinks in the Peninsula. This cycles the depth of the cave formation due to mixing corrosion over a range of depths. This glacial-interglacial cycling of sea level has resulted in stacked tiers of caves within the platform with some above current flooded level, but most lower down in the platform. For a given sea level, only some of the caves are at the right level to discharge freshwater through outlet springs into the sea (**Figure 2**). At lower sea levels, the higher elevation caves are drained and air filled, and thus hydrogeologically abandoned. At higher sea level, even high elevation caves may be flooded by marine water, or at least impeded from discharging freshwater. Along with sea level, however, coastal bathymetry dictates the location of springs discharging freshwater. On the very shallow gradient of the north coast, even a small change in sea level of 1-3 m will result in significant lateral displacement of the optimal coastal discharge point, as the coastline may move 100-1000's of meters on/offshore (see **Figure 2**). In contrast on the Caribbean coast with a more vertical bathymetry, there will be little lateral movement of the effective coastline given such a slight change in mean sea level.

Another factor to consider when trying to identify relic springs is the underlying geology. Intersections of fractures are known to host many of the largest magnitude springs in karst geology. This is expected to be the case along the Caribbean coast of the Peninsula where there is limited deposition of sediments to mask the rocky coastline. The famous *caletas* (bedrock estuaries or lagoons) of Xel Ha, Yal Ku, and Xcaret (see **Figure 1A**) are all situated at the intersection of regional scale fracture lines and discharge significant fresh groundwater from well-developed cave systems. Many of the caletas and other smaller coastal discharges supported major Maya trading ports despite their relatively poor soils[14] (see below). The north coast of Quintana Roo has even more pronounced fracture sets as it is the northern end of the Holbox Fracture Zone, characterized by linear (N/S) swales and depressions, in which wetlands have formed, that extend more than 150 km to the south.

[Controls on Coastal Freshwater Discharge]

While climate may seem an obvious control on groundwater flows, and how much may be discharging along the coastline, the aquifer in northern Quintana Roo is so large in volume, that even very large hurricanes only affect the coastal discharge for days to ~ one week[5,6]. Thus, only multi-year droughts are likely recorded in the coastal sediments. The two primary sub-decadal controls on freshwater discharge are sea level, and the cave geometry of the stacked tiers of caves[4,5]. Our investigation focuses on sea level as the most significant control on whether a spring has been flooded by marine water and rendered incapable of discharging freshwater.

The impact of sea level is amplified when one recognizes that the Yucatan Platform is tectonically stable and that the Late Quaternary vertical displacement has been negligible. This is based on a suite of dated coral deposits from near Cancun[15], sediment records from cenotes in the vicinity of Tulum (130 km south of Vista Alegre) that plot on the global sea-level curve[16], and the depth of dated paleontological and human remains (i.e., the skeleton Naia) recovered from the deep underground sinkhole Hoyo Negro[17]. All available evidence points to the north coast of Quintana Roo as being at the same relative elevation over the last 12,000 years, all while sea level continued to rise to the present modern msl.

With the melting since the last glacial maximum ~12,000 years ago, global sea level initially rose rapidly, but sea levels have still been rising over 2 m over the last 3000 years[18-20]. This most recent gradual rise is significant along the north coast as the low gradient could lead to 100-1000 m of spatial displacement of the coastline and springs. However, local sea level may vary significantly from the global trend, and this is true for our locale in the Western Caribbean[21-22]. The issues of scaling down from global trends to local sites have been recognized in the existing literature on climate and sea-level change in the Maya area[22-24]. Of particular concern is the growing number of high-resolution sea-level records revealing multiple transgressions with some short-term drops in sea level even though overall it is rising (see Thompson and Worth[25] for an example from the Southeastern U.S.). This question of spatial and temporal resolution of the local sea-level record is of particular interest to our research, where the interruption of a unique freshwater supply may occur, causing Maya coastal settlements to have to adjust not only to the shifting coastline, but also the salinization and disappearance of coastal springs. A productive spring 2000 or 3000 years ago may now be a vestigial feature 1-2 m underwater, with only residual discharge under extreme low sea levels. Finding drowned and vestigial springs represents a significant challenge particularly along the northern coast where they may be rapidly buried in sediment.

Key to locating these relic springs is an understanding of tidal cycles. Tides are ~30 cm on the Caribbean coast increase progressively around to the north-west coast. In all cases, the semi-diurnal tides are small compared to the annual cycles driven by the global ocean circulation around the Peninsula and into the Gulf of Mexico. The annual sea level low occurs within the dry season, but the exact timing varies by a few weeks from year to year[5,6]. Vestigial springs may still discharge some groundwater during the annual low sea level, and this stage represents our best modern analogue for the paleowater resources compared to 2000-3000 years ago at the site when global sea levels were lower than present. As we discuss below, this is a focus of our continued research in the area.

SIDEBAR

[Geoarcheology Requires Local Sea Level Records on Low- Lying Coastlines]

While environmental forcings that operate on regional scales (e.g. 100-1000 km) may be reflected in synchronized (re)occupations and abandonment of nearby sites, it is important to recognize that sections of coastlines may be subject to differential sea level forcing due to a number of processes that operate on a sub-regional scale (1- 100’s km):

- Distinct relative sea level histories may occur on different sides of plate boundaries.

- Spatial-temporal variations in glacio-eustatic adjustment across basins, for example at sites around the Caribbean and Gulf of Mexico basins[26].
- Alluvial sediment delivery particularly from large drainage basins reaching the continental interior (e.g. the Mississippi) are subject to sometimes distant climate and tectonic controls on sediment weathering and transport to the marine margin. The balance between alluvial sediment delivery and coastal erosion and subsidence may result in locally prograding or retreating coastlines.
- Geology matters, with contrasting coastline responses at geological contacts. Non-lithified and organic sediments are particularly prone to erosion and/or compaction. In contrast, lithified platforms are more resistant to mechanical and biological erosion.

The interpretation of coastal archeological sites, therefore, is ideally based on local relative sea level reconstructions, and basin-scale sea level records must be used cautiously. Within the Gulf of Mexico basin, variable sea level responses have been documented over sections of the north coast[27], and interestingly are also providing increasing evidence of a relative sea level "overshot" of modern levels in the mid-Holocene[28]. For our site Vista Alegre located on the lithified carbonate Yucatan Platform, and on the distinct Maya tectonic plate, we are working towards a high-resolution local relative sea level curve. Our efforts and those of other working groups benefit from well-preserved datable material on this karst landscape, where sinkholes and caves preserve undisturbed sediments and now flooded stalagmites[29].

Thousands of sinkholes – locally called cenotes – are found across the Yucatan Peninsula although no complete census exists as of yet. Natural access to groundwater is possible through cenotes, which may be open water pools at the ground surface, or may involve some caving at sites away from the coast with even 100 m drop to the water table in the southwest of the Peninsula. Inland ponds called *aguadas* form where the water table lies at the ground surface. A notable alignment of extensive aguadas is located within the wetlands associated with the Holbox Fracture Zone. This area is particularly rich in groundwater, which is one of the reasons the modern city of Cancun was built where it was. The abundance of freshwater inland and the close proximity of the water table to the ground surface[30] does not apply along the north coast.

In addition, the potability of the natural ground water varies from site to site, and systematically with distance from the coast. Site-specific conditions that can render water unpotable include natural deposition of organics falling into the open water sites, or bat guano in enclosed sites. Two aspects of total dissolved solids are large factors in potability. First, the dissolved limestone creates very hard water throughout the whole Peninsula. This has significant health impacts, particularly on kidney function and formation of kidney stones. Second, the salinity due to mixing with intruding marine groundwater leads to the "fresh" water even some kilometers from the coast being somewhat brackish, although probably tolerable at sites >1 km from the coast. Whereas, elevated levels of salinity are observed at sites <500 m from the Caribbean coast (**Figure 3**). As we discuss below, this certainly seems like an issue for the inhabitants of Vista Alegre.

[Water Management amongst the Coastal Maya]

A general overview of Precolumbian water resource management in the Maya area is not necessary given Wyatt's[11] recent overview of the topic in this journal. As he highlights, the ancient Maya employed a multitude of strategies ranging from making use of natural resources like cenotes, lakes or rivers to managed strategies at the household level like *chultunes* to those at the communal levels like the reservoirs at Tikal. The research on these strategies has mainly been focused on what these water management strategies reveal about social organization and their links to political power[31-33]. This focus on water resources does not seem to have translated to coastal research. Coastal researchers have had other topics of focus, and there seems to be an implicit assumption that if there is evidence of people, then they must have had access to water. While we do not deny the logic of that assumption, we do think that problematizing water access is an important avenue for research that can potentially shed light on how these coastal sites were managed and whether or not there may have been a cyclical nature to the occupation of coastal settlements that was strongly controlled by freshwater access.

In our review of the literature on freshwater accessibility by coastal Maya populations, we have noted three themes. The first is the variability in freshwater procurement strategies by coastal populations. A Precolumbian well was noted on Ambergris Cay in Belize (Elizabeth Graham, personal communication, 2015), coastal springs near sites on the east coast of the Yucatan[14,34], river mouths for other coastal sites in Belize, and the use of rainwater harvesting. The mention of rainwater harvesting leads to the second theme we noted in the literature, the use of modern strategies by coastal residents to serve as a proxy for Precolumbian strategies. As already mentioned, the hydrogeology of coastlines are dynamic and can change dramatically over the centuries; therefore extreme caution must be used when applying modern-day analogies. The third theme we noted was the anecdotal nature of much of the above evidence. While a more careful consideration of the spatial and temporal patterning of coastal water management strategies would be of great use, it is beyond the scope of this article. We do, however, highlight a few examples to draw attention to the complexity of the issue of studying coastal freshwater access in the past.

Though we must be careful not to confuse groundwater accessibility with potability, it is necessary to identify and evaluate those hydrogeomorphological and cultural features associated with coastal groundwater access. As mentioned, the well-documented coastal port sites of Xcaret, Xelha, and Yal Ku were somewhat unique as they were situated around major coastal discharges. Of course, their rocky caletas served as ideal harboring locations as well. Though not uncommon along the East coast of the Yucatan Peninsula, these brackish inlets were far from ubiquitous (see above). Nevertheless, there was a nearly continuous corridor of regional coastal settlement crossing a range of karst terrains – even those where potable water was not nearly as accessible.

In the case of Xcaret, Andrews and Andrews[14] suggested that closure of the rocky port during storms or rough seas gave purpose to the nearby site of Xamanha (now the location of modern day Playa del Carmen), which would have afforded ancient canoes with an alternative beach landing. During their intensive 400 ha survey of the site, Silva Rhoads and Hernandez[35] recorded a number of small cenotes and human-made wells that would have been relied upon by Xamanha's residents. The geographically (and therefore commercially and politically) strategic nature of Xamanha, both as a port of embarkation for the island of Cozumel as well as an alternate port for Xcaret, would have compelled residents to adapt to potentially more challenging potable water access realities.

Surprisingly little has been published on groundwater resources at the well-known site of Tulum, though access to potable water in and around the cliff-top site core appears to have been difficult. In contrast, Tulum's sister site of Tancah to the north may have provided more ready access to potable water via a number of cenotes. The well-documented Tancah Cave serves as an entrance to Sistema CUTS (acronym for Cenote Under the Sea), which is connected to Sistema Sac Actun (the second longest surveyed underground river system in the world). Nearby discharges include Casa Cenote (also known as Cenote Tancah, and Cenote Manatí) and Punta Tulsayab, meaning "where the waters go out" (Reference 34, p88).

The situating of sites (their monumental cores, facilities, and associated settlement) along the northeastern and central eastern coasts of the Peninsula was certainly influenced by a range of factors (and not exclusively by abundant or readily accessible sources of potable water). It is therefore incumbent upon the archaeologist to question assumptions about the cultural geography of the region with respect to freshwater. In a time of burgeoning trade, the production and distribution of commodities and other goods compelled coastal sites to both take advantage of certain opportunities and mitigate site-specific challenges. As evidenced by north coastal sites like Emal[36,37], the access to marine resources and the value of salt and the high level of productivity afforded by the region's expansive *salinas* placed coastal inhabitants in an otherwise precarious and marginal environmental zone, in regards to maize cultivation and water access. While one coastal spring has been noted in close proximity to the site (personal communication, Scott Johnson, 2014), there is much we do not know about how the ancient inhabitants of Emal supplied themselves with freshwater in the hypersaline waters of the Río Largartos estuary. As mentioned, this lack of knowledge applies to the majority of coastal Maya sites, including Vista Alegre. Without the evidence for significant infrastructure dedicated to rainwater capture[11,32], does that mean coastal populations were limited in size by freshwater accessibility? Or, were there major efforts made by powerful inland polities like Chichén Itzá to provision coastal sites with water to facilitate circum-peninsular trade? Or, was this trade seasonally restricted due to freshwater accessibility? These are type of research questions that we are investigating at Vista Alegre.

[Vista Alegre – North Coast Paleohydrology]

At the northeast tip of the Yucatan Peninsula – where the Caribbean meets the Gulf – lies the ancient Maya port site of Vista Alegre. The inhabitants of this site, much like the people living nearby today, were forced to contend with the challenging coastal environment of Laguna Holbox, also referred to as Laguna Conil. The "lagoon" is framed to the north by the long, thin island of Holbox and by the mainland coast to the south, which is characterized by flooded mangrove forest and north/south running wetlands. As mentioned above, this mosaic of low-lying, non-arable zones makes access to potable water a challenge for much of the year, a situation that persisted well into the 20th century and contrasts with the Caribbean coast, as noted above.

[Vista Alegre Site Description and Culture History]

The boundaries of Vista Alegre are essentially defined by its geographic setting. An estuary encircles the majority of the low-lying island. The southern portion of the site includes mangrove, *tintal* (dyewood ecosystem), and tidal flats, and to the east and west lie expansive wetlands. The island covers approximately 16 ha. The site itself is in a forested area of locally "high" topographic relief (< 2 m amsl), certainly a relative metric along the low-lying north coast. In general, the overall physiographic setting of Vista Alegre is ideal for a port site with sheltered bays flanking the island. Shelter is an issue even inside the protected Holbox Lagoon, as we ourselves have been buffeted by the *nortes* – winds that at times close the small, modern port at neighboring Chiquilá.

Since 2005 we have registered and mapped a total of 33 structures and features, including platforms, mounds, and a principal pyramidal structure, which dominates the central plaza. The steep-sided pyramid measures 11 m tall and appears to have been damaged by both looters and hurricanes. Along with the pyramid, two other features are particularly interesting. One is a wall that traverses the island east/west and terminates in the harbor areas on both sides of the islands. The other is an *andador*, or walkway, that runs from the southern portion of the island 1.4 km across tidal flats onto the mainland and terminates at collapsed Maya structure.

Our preliminary archaeological fieldwork along the coast has revealed artifacts and features that evidence almost 3000 years of human habitation, ranging from the Middle Preclassic period (800-400 B.C.) to the early 20th century. For those not familiar with Maya archaeology, relative site chronologies are constructed based on stylistic changes in pottery. These changes are pegged to absolute chronologies at certain sites to help anchor these more relative sequences. At this point in time, our occupational history is based predominantly on these relative chronologies, but as we move forward with our interdisciplinary project, it is imperative that we more tightly correlate our cultural history with the environmental data collected. With that caveat, what is clear is that the occupational history of Vista Alegre was not continuous over the past 3000 years. Our research has revealed four periods of occupation between the Middle Preclassic (800/700-400 B.C.) and Postclassic periods (A.D. 1100-1521) with the two major periods corresponding to the Terminal Preclassic and Early Classic (AD 75 – 400) and the Terminal Classic (AD 850 – 1100) periods (for further discussion of the site's settlement history including a timeline of occupation as it is presently known[38,39]).

In addition to the archaeological features mentioned above, there are a few channels or natural fractures in the bedrock that are interesting to note as they might have been modified by the Maya for navigation of trading canoes and access to freshwater at the site. The longest and most easily visible in remote sensing imagery is a linear channel located directly to the northwest of the site. It runs for about 800 m and frames the northern side of a hypersaline, shallow basin. If used by canoe traffic, this cut would have allowed boats to avoid the shallow shoals directly north of Vista Alegre. A smaller channel to the northeast of the site would also have allowed boats to avoid the shoals and move from the main body of the lagoon to the harbor area. The final channel is not as straight as the other two and meanders 250 m from the southern end of the western harbor area to Río Xuxub. As we discuss below, it is the southern portion of Río Xuxub where the freshest water (although still not potable) was identified during our geochemical survey.

[Results – Water Chemistry Analysis in the Present]

A first pass in our search for coastal discharge springs that may have supported coastal settlement included mapping coastal water salinity and temperatures in the dry and wet seasons. Field methods included canoe and kayak-side transects for physico-chemical characterization of accessible surface and groundwater using a calibrated multi-parameter probe (Hydrolab). The information included data on water temperature, conductivity/salinity, pH, dissolved O_2, and Eh (redox). The two principal signatures for discharging fresh groundwater are salinity and temperature as the Yucatan groundwater is 2^{o}C cooler than the coastal marine water[5,6]. In addition to identifying possible springs, these data are critical for creating a profile of the seasonal variability of freshwater in the region.

This waters surrounding Vista Alegre have strong seasonality of water chemistry. There are high volumes of meteoric water input during the rainy season (Jun-Nov) and significant evaporation during the dry season (Dec-May). In May 2011 at the end of the dry season, the waters surrounding Vista Alegre were all very warm (26-36 °C) and hypersaline (39.2 – 65.9 psu, compared to normal of 36 psu for sea water) with the warmest, saltiest water the farthest inland. Maximum salinity values of 65.9 psu were measured in the mangrove "dead zone" (**Figure 4**). This indicates evaporation is an important control as the freshwater inputs evolve into hypersaline water during the dry season. In December 2011 at the end of the rainy season, the water temperatures were slightly lower (24-34 °C) and the salinity was much lower, ranging from 3.3 - 24.2 psu. The distribution of the salinity was reversed compared to the May observations. The freshest water was found the farthest inland with salinity increasing outward into the lagoon – typical for the mixing of seawater and fresh meteoric water.

[Results – Sediment Cores]

The contemporary water chemistry provides critical baseline data for our analysis of the sediment cores. We collected 12 manual push-cores from the shallow waters surrounding Vista Alegre, which have been analyzed at 1 cm resolution using standard methods for Loss on Ignition (LOI), $\delta^{18}O_{carb}$ and $\delta^{13}C_{carb}$ of bulk carbonate, granulometry, micropaleontology, and AMS radiocarbon dating. The sediment cores have so far been dated with 34 C^{14} dates on 7 of the 12 cores. The mangrove shorelines and shallow bays around Vista Alegre are mantled in well-preserved sedimentary sequences. This project provides records of past water salinity using two powerful proxies applied to the cores. First is the use of stable isotope analysis on the oxygen molecules in the carbonate portion of the core sediments ($\delta^{18}O_{carb}$). The isotopic composition of geological materials reflects the source materials (such as the water in which it formed) and processes to which they have been subjected. These data are then compared to the oxygen $\delta^{18}O$ values of freshwater and seawater today[40-44]. Meteoric precipitation is isotopically lighter than seawater[45]. By extension, the fresh groundwater recharged by meteoric water will discharge isotopically light waters into the coastal seawater. When these datasets are combined we get a paleosalinity index. Second, the different species of microscopic foraminifera, single-cell marine and brackish organisms that are present worldwide and are commonly used for environmental reconstructions, and thecamoebians, single cell freshwater organisms used for the same purpose, preserved in the sediment are highly selective for specific salinity ranges. Our preliminary cores' sediments confirmed the preservation of abundant, well-preserved micropaleontological species with varying salinity tolerances. The separation from the core sediments, counting of species types and abundances, followed by $\delta^{18}O_{carb}$ on them, provides the "gold standard" of paleosalinity reconstruction[43,46].

The modern surface community assemblages of foraminifera are used as an analogue for past conditions. In this study, the assemblages provide a proxy for shoreline and sea-level reconstruction at the site. Previous works elsewhere have used surface sample assemblages as an indicator for zonation in marshland and mangrove areas[47-51], and in this study this approach is being used to reconstruct the site's environmental settings over time. From the results to date, we can observe changes in the foraminifera assemblages within changing layers in the cores, as well as between different cores and surface samples. These results tell us about different microenvironments, i.e., zonation of the site at present, and support the argument that environmental changes have occurred across the site in different time periods. For example, we observe some foraminifer types, such as *Laevipeneroplis,* that are present at some horizons in the cores, but absent in others, which is an indicator of environmental change that can be related to shifts such as water chemistry variation, sea-level change, and shoreline movement. In many horizons in the cores we observe changing ratios and relative abundance between the same foraminifers, *Elphidium*, *Quinqueloculina* and *Miliolinella*; that may reflect particular environmental changes. In several samples with lower total foraminifera abundance we find higher proportions of *Ammonia*, a genus with certain species known to have wide environmental tolerances, and therefore indicative of transitional or high-stress conditions such as lower or higher than typical salinities. A few core intervals have no foraminifera present whatsoever (and no marine fauna in general). One possible reason is that the interval was terrestrial at the time it was deposited, an alternative explanation is that post-depositional dissolution of the calcareous foraminifera occurred due to lower pH levels, such as those sometimes present in mangrove soils[52-54]. We try to differentiate between these two options by looking for mangrove evidence in the sample, and using other proxies such as grain size, LOI analysis and calcite precipitation from the sediment. The sediments are presenting useful information and, generally, well-preserved foraminifera, which allow for a detailed environmental reconstruction of the site.

Within each core, shell beds correlate with high salinity based on the oxygen isotopic data and are interpreted as sea-level highstands. Fine grain intervals in between the shell beds have lower carbonate content and are interpreted as sea-level lowstands. Four alternating pairs of these beds lie beneath a mangrove peat cap. The strata are continuous between the three of the cores based on carbon-14 dates. As demonstrated in Core 9, retreat of freshwater correlates with the base of each of the shell beds, suggesting they are transgressive cycles of sea-level rise (**Figure 5**). They have a consistent 500 year cyclicity correlated across all of the cores.

Overall, the chemical proxies, lithology, and paleosalinity model reconstructed to date reveal four onlapping parasequences representing an overall transgression of the coastline with strong seasonality of water chemistry that has been changing under the control of rising sea levels over the past 3000 years. The sedimentation rate and timing of the transition to marine is in reasonable agreement with local sea-level curves[55] meaning that the shoreline and possible terrestrial features during some of the occupational phases of Vista Alegre are most likely drowned today. The isotope record indicates large changes in the proportion of freshwater and high evaporation rates have occurred throughout the site's history. Superposition of these seasonal cycles on the long-term rise in sea level means that water may have been much more readily accessible to the Maya who inhabited this site than it is today.

Conclusion

While there is still much work to be done in our investigation of freshwater access at the ancient Maya port site of Vista Alegre, some intriguing patterns have emerged. As discussed, the rise in sea level and the abundance of meteoric water appear to be inversely related over the past 3000 years. This is not surprising given what we know about the hydrogeology of the Yucatan. What is interesting is how these preliminary data correlate with our settlement history of the site[39]. As indicated in **Figure 5**, there are four periods of high sea stands where there is limited freshwater at the site. The first of these dates to the middle of the third century B.C. This is a time period when we do not have much evidence for people living at the site. Based on the ceramic data, it appears as though people repopulated the island in the first century A.D., a time period when freshwater was more abundant. The next high sea stand, however, seems to have occurred when the site still had a robust population. This high sea stand has been linked to the abandonment of the interior of the Yalahau region[30] due to the impact it would have had on the interior wetlands that were actively managed by the ancient Maya for agricultural purposes[56,57]. The third high sea stand does seem to correlate with the other period of depopulation at the site. In fact, we have found some evidence that indicates the site's inhabitants were trying to build-up the western portion of the island during 7th century A.D., perhaps in response to rising sea levels. After being abandoned for the better part of a century, the site is again reoccupied during a period when freshwater seems to have been locally abundant. It is during the 9th through 11th centuries A.D. that Vista Alegre became engaged in long-distance trade and connected to major inland powers like Chichén Itzá. However, the site is again abandoned at some point toward the beginning of the 12th century A.D. Was this a result of rising sea levels and the decreasing availability of freshwater at the site or more tightly connected to broader geopolitical shifts that mark Chichén Itzá's decline as a regional power, or are the cultural and natural processes related?

This is one line of inquiry that we will continue to follow as our project moves forward. By correlating multiple facets of the changing paleoenvironment with broader social and economic changes, the PCE research team will continue to investigate the challenges faced, and opportunities pursued, by these coastal peoples as they adapted to their changing coastal landscape. This episodic settlement history at Vista Alegre provides tantalizing clues to the vulnerabilities and resilience of these coastal peoples. We also hope that the interdisciplinary research program described here provides others with a template to more critically evaluate coastal water access in the past, so that we can more clearly elucidate the scope of human ingenuity or the limitations placed on that ingenuity by the scarcity of potable water.

Acknowledgements

We thank the Consejo de Arqueología of Mexico's National Institute of Anthropology and History (INAH), and Adriana Velazquez Morlet and the Quintana Roo division in particular. Our research was made possible through the financial support of the National Oceanic and Atmospheric Administration (NOAA) with the guidance of Frank Cantelas in the Office of Exploration and Research (OER) and web coordinator and field operations specialist Emily McDonald, the Waitt Institute, and the Initiative for Sustainability and Energy (ISEN) at Northwestern. This project has benefited from the generous help from the people of the Chiquilá and San Ángel ejido, and all of the members of the Proyecto Costa Escondido at large.

References

1. Andrews AP. The role of trading ports in Maya Civilization. In *Vision and Revision in Maya Studies*, edited by Clancy FS, Harrison PD, Albuquerque: University of New Mexico Press. 1990. 159-167.

2. Sabloff JA. Old myths, new myths: The role of sea traders in the development of ancient Maya civilization. In *The Sea in the Pre-Columbian World*, edited by Benson EP, Washington, D.C.: Dumbarton Oaks. 1977. 67-95.

3. Beddows PA. *Cave Hydrology of the Caribbean Yucatan Coast*, Austin: Bulletin 11 Association of Mexican Cave Studies. 2003.

4. Smart PL, Beddows PA, Doerr S, Smith SL, Whitaker FF. Cave development on the Caribbean coast of the Yucatan Peninsula, Quintana Roo, Mexico. *Geological Society of America Special Paper 404: Perspectives on Karst Geomorphology, Hydrology, & Geochemistry* 2006.

5. Beddows PA. *Groundwater hydrology of a coastal conduit carbonate aquifer: Caribbean coast of Yucatán Peninsula, México.* Unpublished Ph.D. dissertation, University of Bristol, UK. 2004.

6. Beddows PA, Blanchon P, Escobar E, Torres-Talamante O. Los cenotes de la península de Yucatán. *Arqueología Mexicana* 2007, 16:32-35.

7. Glover JB. *The Yalahau Regional Settlement Pattern Survey: A Study of Ancient Maya Social Organization in Northern Quintana Roo, Mexico*. Unpublished Ph.D. dissertation, Department of Anthropology, University of California, Riverside. 2006.

8. Glover JB. The Yalahau Region: A Study of ancient Maya socio-political organization. *Ancient Mesoamerica* 2012, 23:271-295.

9. Rissolo D. *Ancient Maya Cave Use in the Yalahau Region, Northern Quintana Roo, Mexico*. Austin: Bulletin 12 Association for Mexican Cave Studies. 2003.

10. Chamberlain RS. *The Conquest and Colonization of Yucatan, 1517-1550*. Washington, D.C.: Carnegie Institution. 1948.

11. Wyatt AR. The scale and organization of ancient Maya water management. *WIREs Water* 2014, 1:449-467.

12. Ford DC, Williams PD. *Karst Hydrogeology and Geomorphology*. New York: John Wiley and Sons. 2007.

13. Worthington SRH, Ford DC, Beddows PA. Porosity and permeability enhancement in unconfined carbonate aquifers as a result of solution. In *Speleogenesis: Evolution of Karst Aquifers*, edited by Klimchouk A, Ford DC, Palmer A, Dreybrodt W. St. Louis: Cave Books. 2000. 463-471.

14. Andrews IV EW, Andrews AP. *A preliminary study of the ruins of Xcaret, Quintana Roo, Mexico, with notes on other archaeological remains on the Central East Coast of the Yucatan Peninsula*. New Orleans, LA: Middle American Research Institute Publication 40. 1975.

15. Szabo BJ, Ward WC, Weidie AE, Brady MJ. Age and magnitude of the late Pleistocene sea-level rise on the eastern Yucatan Peninsula. *Geology* 1978, 6:713-715.

16. Gabriel JJ, Reinhardt EG, Peros MC, Davidson DE, van Hengstum PJ, Beddows PA. Palaeoenvironmental evolution of Cenote Aktun Ha (Carwash) on the Yucatan Peninsula, Mexico and its response to Holocene sea level rise. *Journal of Paleolimnology* 2009, 42:199-213.

17. Chatters JD, Kennett DJ, Asmerom Y, Kemp BM, Polyak V, Nava Blank A, Beddows PA, Reinhardt E, Arroyo-Cabrales A, Bolnick DA, Malhi RS, Culleton B, Luna Erreguerena P, Rissolo D, Morell-Hart S, Stafford TW. Late Pleistocene human skeleton and mtDNA from Mexico links Paleoamericans and modern Native Americans. *Science* 2014, 344:750-754.

18. Chappell J, Shackleton ND. Oxygen isotopes and sea level. *Nature* 1986, 324:137-140.

19. Fairbanks RG. A 17,000-year glacio-eustatic sea level record: Influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature* 1989, 342:637-642.

20. Lambeck K, Chappell J. Sea level change through the last glacial cycle. *Science* 2001, 292(5517):679–686.

21. Cooper J, Peros M. The archaeology of climate change in the Caribbean. *Journal of Archaeological Science* 2010, 37:1226-1232.

22. McKillop H. *Salt: White Gold of the Ancient Maya*. Gainesville: University Press of Florida. 2002.

23. Dahlin BH. Climate change and the end of the Classic Period in Yucatan: Resolving a paradox. *Ancient Mesoamerica* 2002, 13:327-340.

24. Dahlin BH, Andrews AP, Beach T, Bezanilla C, Farrell P, Luzzadder-Beach S, McCormick V. Punta Canbalam in context: A peripatetic coastal site in northwest Campeche, Mexico. *Ancient Mesoamerica* 1998, 9:1-15.

25. Thompson VD, Worth JE. Dwellers by the Sea: Native American adaptations along the southern coasts of eastern North America. *Journal of Archaeological Research* 2011, 19:51-101.

26. Milne GA, Peros M. Data–model comparison of Holocene sea-level change in the circum-Caribbean region. *Global and planetary change* 2013, 107:119-131. DOI: 10.1016/j.gloplacha.2013.04.014

27. Anderson JB, Wallace DJ, Simms AR, Rodriguez AB, Milliken KT. Variable response of coastal environments of the northwestern Gulf of Mexico to sea-level rise and climate change: Implications for future change. *Marine Geology* 2014, 352: 348–366. doi:10.1016/j.margeo.2013.12.008

28. Balsillie JH, Donoghue JF. Northern Gulf of Mexico sea-level history for the past 20,000 years. In *Gulf of Mexico Volume 3 Geology - Origin, Waters and Biota*, edited by Buster NA, Holmes CW. 2014, Texas A&M University Press, College Station, TX, pp. 53-72.

29. van Hengstum PJ, Onac BP, Richards DA, Dorale JA, Coastal sinkholes and caves. In *Handbook of Sea-level Research*, edited by Horton BP, Long A, Shennan B. 2015, John Wiley and Sons, pp. 83-103.

30. Fedick SL. A Reassesment of water and soil resources in the flatlands of the Northern Maya Lowlands. In *The Resilience and Vulnerability of Ancient Maya Landscapes: Transforming Maya Archaeology through IHOPE*, edited by Chase AF, Scarborough VL. Archaeological Papers of the American Anthropological Association, Number 24. Hoboken, N.J.: Willey and Sons Publishing. 2014, pp. 72-83.

31. Lucero LP. *Water and Ritual: The Rise and Fall of Classic Maya Rulers* Austin: University of Texas Press. 2006.

32. Scarborough V. *The Flow of Power: Ancient Water Systems and Landscapes.* Sante Fe, N.M.: School of American Research Press. 2003.

33. Scarborough V. Beyond sustainability: Managed wetlands and water harvesting in Ancient Mesoamerica. In *The Archaeology of Environmental Change: Socionatural Legacies of Degradation and Resilience*, edited by Fisher CT, Hill JB, Feinman GM, Tucson: University of Arizona Press. 2009. pp. 62-84.

34. Miller AG. *On the edge of the sea: mural painting at Tancah-Tulum, Quintana Roo, Mexico*. Washington, D.C.:Dumbarton Oaks. 1982.

35. Silva Rhoads C, Hernández CMdlC. *Estudios de patrón de asentamiento en Playa del Carmen, Quintana Roo*. México, D.F.: Instituto Nacional de Antropología e Historia (INAH). 1991.

36. Johnson S. *Proyecto Arqueológico Emal: Estudio de una Puerta y Salinera Prehispánico*. Annual Technical Report submitted to the Consejo de Arqueología del Instituto Nacional de Antropologa e Historia (INAH). 2014.

37. Kepecs S. *The Political Economy of Chikinchel, Yucatan, Mexico: A Diachronic Analysis from the Prehispanic Era through the Age of Spanish Administrative.* Unpublished Ph.D. dissertation, Department of Anthropology, University of Wisconsin, Madison. 1999.

38. Glover JB, Rissolo D, Ball JW, Esteban Amador F. Who were the Middle Preclassic settlers of Quintana Roo's north coast? New evidence from Vista Alegre." *Mexicon* 2011, 33(3):69-73.

39. Glover JB, Rissolo D, Mathews JP. The Hidden world of the Maritime Maya: Lost landscapes along the north coast of Quintana Roo, Mexico. In *Maritime Cultural Landscapes*, edited by Ford B, New York: Springer. 2011. 195-216.

40. Bigg GR, Rohling EJ. An oxygen isotope data set for marine waters. *Journal of Geophysical Research-Oceans* 2000, 105(C4):8527-8535.

41. Bowen GJ, Wilkinson B. Spatial distribution of delta O-18 in meteoric precipitation. *Geology* 2002, 30(4):315-318.

42. Dansgaard W. Stable Isotopes in Precipitation. *Tellus* 1964, 16(4):436-468.

43. Peros MC, Reinhardt EG, Schwarcz HP, Davis AM. High-resolution paleosalinity reconstruction from Laguna de la Leche, north coastal Cuba, using Sr, O, and C isotopes. *Palaeogeography, Palaeocimatology, Palaeoecology* 2007, 245(3-4):535-550.

44. Wassenaar LI, Van Wilgenburg SL, Larson K, Hobson KA. A groundwater isoscape (delta D, delta O-18) for Mexico. *Journal of Geochemical Exploration* 2009, 102(3):123-136.

45. Sharp Z. The Oceans, biogenic carbonates: Oxygen. In *Principles of Stable Isotope Geochemistry*, edited by Rapp C, Upper Saddle River, N.J.: Prentice Hall. 2007, pp. 103-148.

46. van Hengstum PJ, Reinhardt EG, Beddows PA, Gabriel J. Linkages between Holocene paleoclimate and paleohydrogeology preserved in a Yucatan underwater cave. *Quaternary Science Reviews* 2010, 29:19-20.

47. Edwards RJ, Wright AJ, Van De Plassche O. Surface distributions of salt-marsh foraminifera from Connecticut, USA: Modern analogues for high-resolution sea level studies." *Marine Micropaleontology* 2004, 51:1–21.

48. Edwards RJ, Horton BP. Reconstructing relative sea-level change using UK salt-marsh foraminifera. *Marine Geology* 2000, 169(1-2):41–56.

49. Gehrels WR. Determining relative sea-level change from salt-marsh foraminifera and plant zones on the coast of Maine, U.S.A. *Journal of Coastal Research* 1994, 10(4):990–1009.

50. Horton BP, The Distribution of contemporary intertidal foraminifera at Cowpen Marsh, Tees Estuary, UK: Implications for studies of Holocene sea-level changes. *Palaeogeography, Palaeoclimatology, Palaeoecology* 1999, 149(1-4):127-149.

51. Woodroffe SA, Horton BP, Larcombe P, Whittaker JE. Intertidal mangrove foraminifera from the central Great Barrier Reef shelf, Australia: Implications for sea-level reconstruction. *The Journal of Foraminiferal Research* 2005, 35(3):259–270.

52. Boto KG, Wellington JT. Soil characteristics and nutrient status in a Northern Australian mangrove

forest. *Estuaries* 1984, 7(1):61-69.

53. Bradshaw JS. Environmental parameters and marsh foraminifera. *American Society of Limnology and Oceanography* 1968, 13(1):26–38.

54. Wakushima A, Kuraish S, Sakurai K. Soil salinity and pH in Japanese mangrove forests and growth of cultivated mangove plants in different soil conditions. *Journal of Plant Research* 1994,107(1):39–46.

55. Toscano MA, Macintyre IG. Corrected western Atlantic sea-level curve for the last 11,000 years based on calibrated C-14 dates from Acropora palmata framework and intertidal mangrove peat. *Coral Reefs* 2003, 22(3):257-270.

56. Chmilar JA. *Ancient Maya Cultivation in a Dynamic Wetland Environment: Insights into the Functions of Anthropogenic Rock Alignments at El Edén Ecological Reserve, Quintana Roo, Mexico*. Unpublished Ph.D. dissertation, Department of Anthropology, University of California, Riverside. 2013.

57. Leonard DI. *The Yalahau Regional Wetland Survey: Ancient Maya Land Use in Northern Quintana Roo, Mexico*. Unpublished Ph.D. dissertation, Department of Anthropology University of California, Riverside. 2013.

Figure captions

Figure 1 **A**. A selection of Maya sites in the Lowland Yucatan Peninsula, with emphasis on coastal sites on the Caribbean and north coast. **B.** The port site of Vista Alegre on the north-east shore of the Yucatan Peninsula.

Figure 2 On shallow platform slopes, such as on the north coast of the Yucatan Peninsula, even small changes in sea level may laterally displace the coastline, and affect the function of spring locations. **A.** The coastline and springs were located 10-100's of km from the current shoreline in the early Holocene. **B.** With rising sea levels over the Holocene towards our modern high levels, the lower tiers of caves and now-offshore springs are drowned. Global sea levels have risen 2-3 m in the last 3000 years.

Figure 3 Salinity with distance inland from the Caribbean Coast for sites located south of Cancun and north of Sian Ka'an Biosphere (reproduced from Beddows et al., 2004). All sites located within 0.5 km from the coast are somewhat to very brackish, even grading into marine salinity. Sites further inland than 0.5 km may represent tolerable water supplies. California drinking water limit of ~1.5 mS/cm as horizontal black line. In all cases, rainwater would represent a far superior source of potable water.

Figure 4 Sampled salinity around the Vista Alegre site in May (**left**) and December (**right**) 2011, which is at the end of the dry season and rainy season respectively. Values are in PSU salinity units, where rainwater is <0.5 PSU, and 100% normal marine water is 36 PSU. All sampled waters in May 2011 were hypersaline. Only one sample in December 2011 in the Río Xuxub (lower left of image) was 3 PSU and might be considered potable.

Figure 5 Reconstruction of meteoric water inputs and evaporation rates compared to shell beds. Chronology model shown in leftmost vertical scale, with absolute depth in core (cm) on second Y axis. Occurrence of shell beds correlates with reduced meteoric water determined based on isotopic ^{18}O of the sediments.

Further Reading/Resources

TBD

Related Articles

DOI	Article title
WCC039	The scale and organization of ancient Maya water management

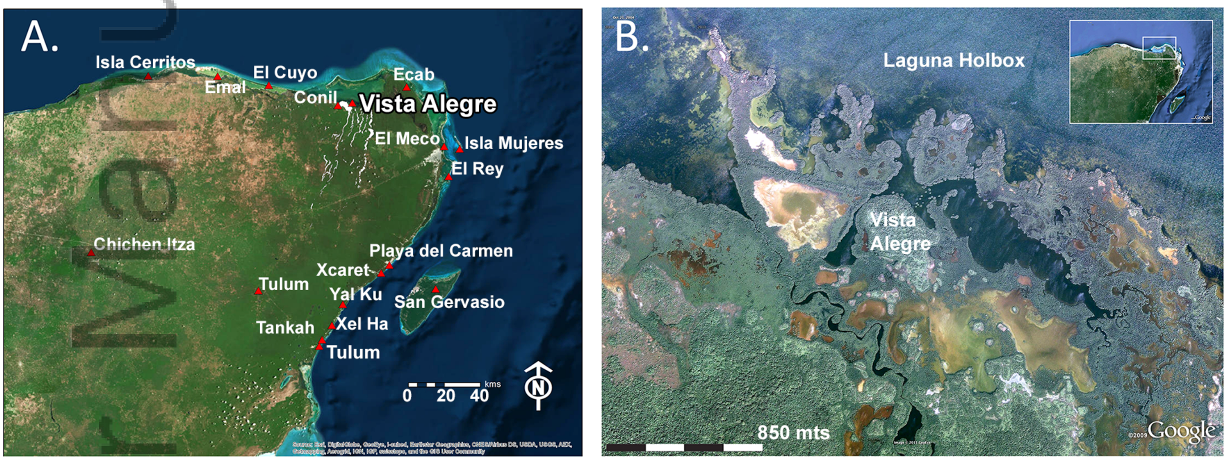

Fig1A_1B_horizont_300dpi_Ed.tif

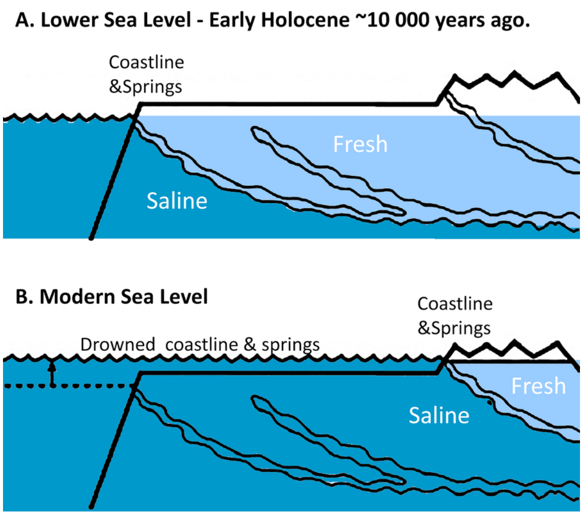

Fig2_600dpi.tif

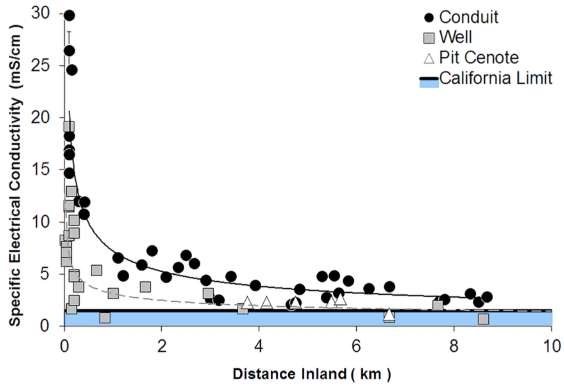

Fig3_600dpi_sal_with_dist.tif

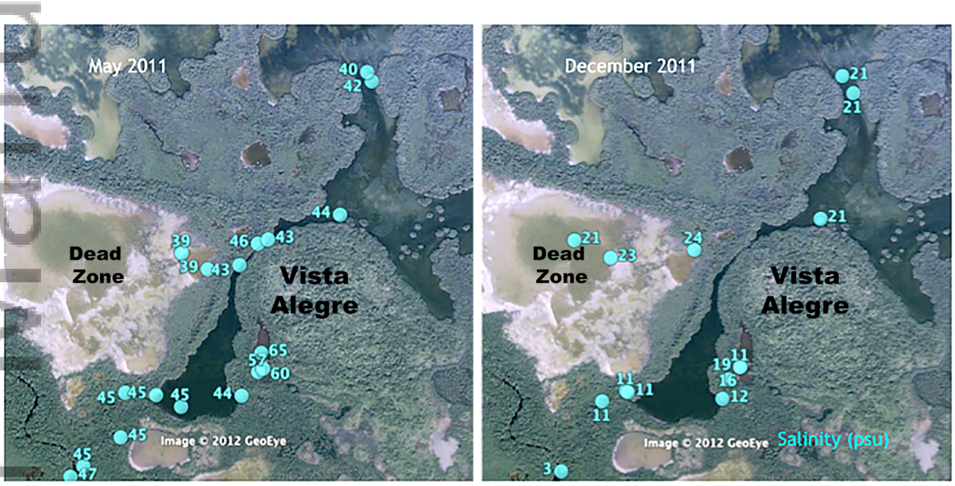

Fig4 - VA_MayDec_Salinity 300dpi.tif

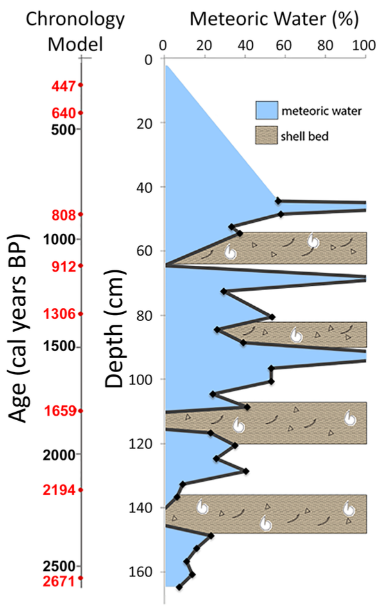

Fig5_600dpi_Core 9_percent meteoric with ages.tif