Coastal reconstruction of Vista Alegre, an ancient maritime Maya settlement

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Abstract

Past coastal reconstruction is useful for understanding archaeological coastal settlements and predicting how coastal change might affect modern populations. The ancient Maritime Maya inhabitants of Vista Alegre in the northeastern Yucatan were active seafaring peoples. However, the past coastal landscape environmental history is unknown. Previous research concentrated on the fully terrestrial component of the site, and did not approach the issue from an earth sciences, sedimentological perspective. In this study, a sediment core campaign in the shallow offshore of Vista Alegre aimed to reconstruct the coastal and environmental changes that occurred over the past 3000 years; and specifically identify the changes in sea-level. Nine cores were analyzed using a multi-proxy approach including a range of sedimentological parameters such as granulometry, micropaleontology (foraminifera), radiocarbon dating, and loss-on-ignition. The sediment cores provided an archive of environmental changes related to sea-level change, anthropogenic influence, and shifting microenvironments which can be associated with cultural time periods. The environmental phases and shifts show some linkage to the archaeological chronology; suggesting an association between the environmental conditions and human activities. Sea-level changes and shifting shorelines have always

been, and still are, a challenge for coastal settlements; and ancient sites can be a harbinger of what to anticipate in the future. In addition to this, current natural and anthropogenic pressures on coastlines are placing archaeological sites at increasing risk and thereby threatening this important scientific and cultural archive; therefore, efforts to identify, characterize, and record them prior to destruction are increasingly important.

Keywords: Geoarchaeology, Sedimentology, Geomorphology, Loss on ignition, Holbox

1. Introduction

1.1 Coastal landscapes

The reconstruction of ancient coastal landscapes can provide information for understanding sea-level trends, anthropogenic impacts on coastal morphology, and human cultural adaptation and development. Coastal archaeological sites are particularly useful for their chronological constraints, and for the interaction of anthropogenic and natural processes (Benjamin et al., 2017; Marriner and Morhange, 2007). Today, a multitude of global issues such as increasing populations in coastal areas and sea-level rise make it imperative to better understand this interrelationship between human activities and sea-level change, and past records are a useful dataset for comparison. At present, coastlines are being disproportionately affected by increased population densities within well-established cities, along with the establishment of new urban coastal centers (Neumann et al., 2015). This trend is due to the logical geographical advantages of the coastal zone that provide access to sea-based trade routes, often more temperate climate, and sometimes access to specific water and food resources (Small and Nicholls, 2003), all of which were true in the past as well as in the present.

However, coastlines are one of the most morphologically dynamic environments, vulnerable to the impacts of rising sea-levels, hurricanes, coastal erosion, floods, and tsunamis. Coastal infrastructure, industry, and resources are therefore regularly threatened (Zhang et al., 2004). For example, global sea-level rise in the late Holocene had major impacts on coastal landscapes (Fairbanks, 1989; Flemming, 1998, Benjamin et al. 2017), and current sea-level rise projections suggest continued trends into the future (Horton et al., 2014; Nicholls and Cazenave, 2010; Rahmstorf, 2007). People in the past, as in the present, faced these issues and had to abandon or adapt to the circumstances (van Andel, 1989; Nicholls and Tol, 2006; Sterr, 2008; Tol et al., 2008).

Studying coastal sites produces a reference set of patterns and trends in environmental or anthropogeniclly driven changes, which may support preparing for the future in an informed manner as well as informing us about the past. Determining what coastal geomorphological changes occurred in response to sea-level change requires more than simply moving the waterline using the known modern topography and bathymetry. While the nature of surface topography or bathymetry certainly reflects some aspects of underlying features, it is not a one-to-one relationship because of both natural and anthropogenic influences on the geomorphology. Environmental influences include differential sedimentation, erosion, infilling, climate, vegetation, and shifting river systems. Anthropogenic landscape modification can be in the form of transport canals, coastal barriers, walls, breakwaters, food procurement installations, and other infrastructure. Therefore, it is imperative to investigate the subsurface of a site and not depend solely on surface features.

1.2 Reconstructing coastal landscapes

Recognizing past coastal configurations and the events that affected them can be done by using multi-proxy studies anchored in sedimentological analysis. For example, a large body of research has focused on sea-level change and the related coastal impacts and transitions (Brinson et al., 1995; Reed, 2002; Traill et al., 2011; Werner and Simmons, 2009). Facies associated with moving environmental zones; such as the location and nature of river mouths, estuaries, bays, as well as changing water depths are recognized with a range of sea-level indicators including coastal peats, beach deposits, and saltmarshes (e.g. Gehrels et al., 2001, 2013; Lambeck et al., 2004). Facies are identified using proxies such as granulometry (grain size), loss on ignition (LOI), micropaleontology including foraminifera, geochemistry, and anthropogenic markers. Examples for anthropogenic sea-level range indicators include harbor-related features, houses, shipwrecks, streets, wells, and other elevation-specific features (Auriemma and Solinas, 2009; Benjamin et al., 2017; Marriner and Morhange, 2006; Morhange et al., 2006, 2001).

Foraminifera are used widely both for environmental reconstruction based on their species assemblage, and for geochemical analysis (Scott et al., 2001). Studies worldwide have used foraminifera assemblages as a sea-level indicator and as a paleoenvironmental marker (e.g., Edwards and Horton, 2000; Gehrels and van de Plassche, 1999; Kemp et al., 2011; Waelbroeck et al., 2002). For example, the relative abundances of the three main order subdivisions of foraminifera (rotalid, miliolid, and textularia), allows for discrimination between marsh, tidal flat, shelf, or deepwater environments, (Armstrong and Brasier, 2005; Hayward and Hollis, 1994; Murray, 1970). Similarly, they have been used at coastal archaeological sites to identify ancient harboring locations (Goodman et al., 2009; Marriner et al., 2005; Morhange et al., 2003; Reinhardt et al., 1994; Reinhardt and Raban, 1999).

Loss on ignition (LOI) is used to estimate the organic and carbon content of soils and sediments (Ball, 1964). For example, LOI at different temperatures varies with proportion of organic matter and carbonate, the latter perhaps due to marine fauna in the sediment. Different studies may use LOI either in a quantitative manner, or in a qualitative manner, or both. The LOI results can show the trend of the organic content in the sediment, and the trend of the carbonates content. These relatively easy and quick to achieve trends, can represent environmental changes that affected the sediment, and as such are used for a variety of studies. The LOI method is widely used to study paleoclimate variability (Hallett and Hills, 2006; Serrano et al., 2012; Weng and Jackson, 1999), events such as hurricanes and droughts

(McCloskey and Keller, 2009; McKee and Cherry, 2009; Nesje and Dahl, 2001), and sea-level studies (Eronen et al., 2001) including in sinkholes and caves (Gabriel et al., 2009; van Hengstum et al., 2011).

Grain size can reflect subtle differences and changes in transport energy and sediment type and source, which typically varies systematically within coastal systems (Boggs, 2011; Carter and Woodroffe, 1997). The interpretation of grain size distributions results, can help discriminate between alluvial and marine sediments as well as storm deposits, beach berms, back lagoons, etc. (Folk, 1966; Folk and Ward, 1957; Friedman, 1961). In some cases, grain size has been used to help define when a harbor was fully functioning and when it was compromised based on changes between the finer-sized sediments present in the lower-energy protected harbor environment versus coarser (relatively) sized grains in the non-protected environment (Goodman et al., 2008; Marriner and Morhange, 2006; Reinhardt and Raban, 1999).

1.3 Maritime Maya

The Maya civilization existed and flourished in Mexico and Central America from c. 2750 yr. B.P until the time of Spanish Contact in the 16th century (Coe and Houston, 2015). Archaeologists have investigated the complex reasons behind the rise and fall of overlapping Maya states (Demarest, 2004; Morley and Brainerd, 1956; Thompson and Eric, 1970); including recent discussions on the significance of droughts in the 9th century contributing at least towards the collapse of some Maya polities (Curtis et al., 1996; Gill et al., 2007; Hodell et al., 2005; Iannone, 2014; Medina-Elizalde et al., 2010). As is the case with archaeological research into other complex societies across the globe, understanding ancient economic systems and trade networks has been a productive research focus.

In the case of the ancient Maya, trade routes spanned land and sea, and connected various parts of the Maya world and Mesoamerica for over three millennia (Masson and Freidel, 2002). Land trade routes, are not always well defined, and sea routes are arguably even more elusive and challenging to discover (Andrews, 1990; Andrews and Corletta, 1995; McKillop, 2002). At present, several examples of maritime Maya infrastructure have been found and explored, such as the site of Isla Cerritos (Andrews and Corletta, 1995; Andrews and Gallareta, 1988). The only artifact of the transport vessels is an oar found in the salt works of K'ak Naab in Belize, and a small canoe likely used for local short distance travel (McKillop, 2005). Large dugout canoes were recorded by Spanish explorers on Columbus's fourth voyage to the New World (Servin, 1959); however, archeological evidence of such have yet to be recovered. While the maritime vessels and trade routes may be elusive, long distance coastal trade is evidenced in the artifact assemblages of coastal sites and major Maya centers like Chichén Itzá, located in the Mexican modern state of Yucatan, and even depicted on murals and other artwork (e.g., Coggins and Shane, 1984; Finamore and Houston, 2010; Glover et al., 2011a).

The maritime Maya site of Vista Alegre is located on the northeastern coastline of the Yucatan Peninsula (Fig. 1). Vista Alegre was first occupied at 2700 yr B.P. by some of the earliest people who can be culturally identified as Maya in the northeastern Yucatan Peninsula (Glover et al., 2011b). Following this early occupation, the site was a bustling coastal town between 2000 and 1600 yr B.P. Population appeared to decline in the following centuries followed by an almost century-long hiatus between 1350 and 1250 yr B.P. After this apparent abandonment, non-local artifact materials found at the site serve as evidence for maritime trade and interaction, and the coastal site of Vista Alegre flourished again as a trading port during the later Terminal Classic period (1100-850 yr B.P; Glover et al., 2011b). Circum-peninsular networks were established and maintained as Maya seafaring merchants moved both commodities and prestige goods between emerging coastal centers. It was during this time that Chichén Itzá extended its control over commercial systems that increasingly connected more distant Mesoamerican peoples (Kowalski and Kristen-Graham, 2007). Vista Alegre's location may have afforded its inhabitants a strategic geographical advantage as a node between Gulf of Mexico and Caribbean coastal sites; particularly as the incentive to facilitate and benefit from maritime commerce increased.

The known excavated portion of the Vista Alegre archeological site at present is located on a peninsula about 16 ha in area (Fig. 1).

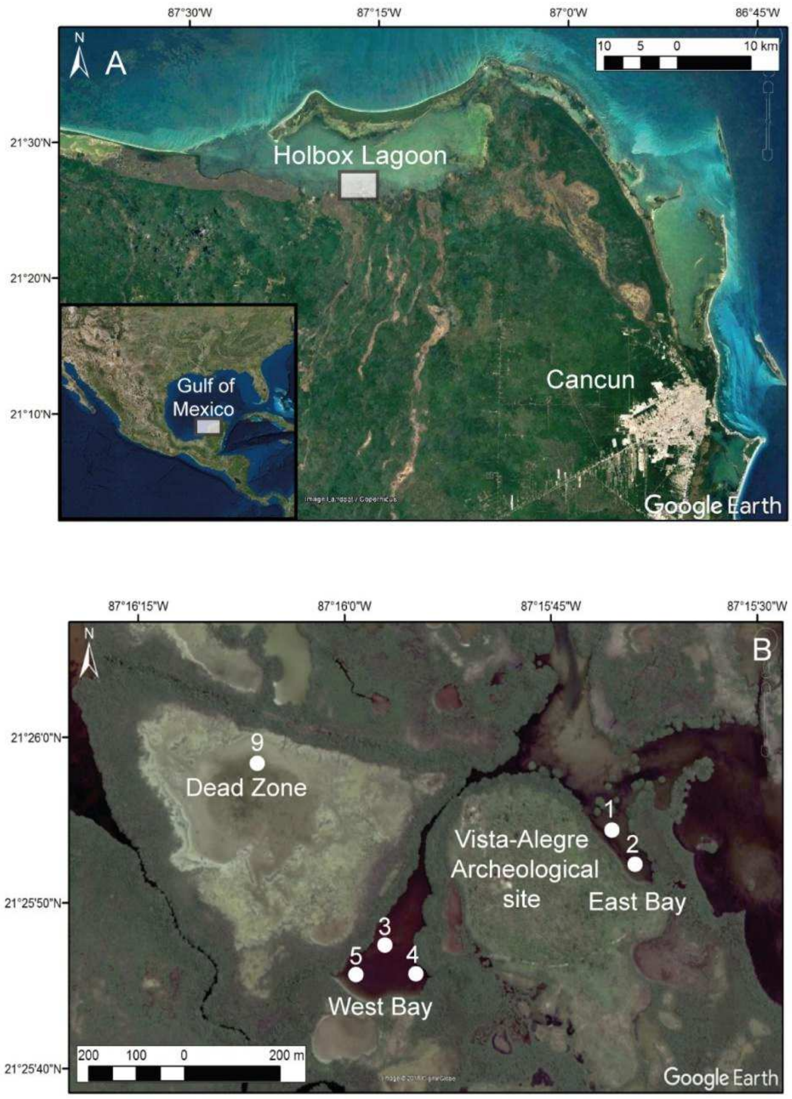

Fig. 1. Study location map. (A) Northeastern Yucatan Peninsula map, regional map at bottom left (inset). White squares indicate site of Vista Alegre. (B) Vista Alegre Maritime Maya archaeological area. White numbered circles represent positions of sediment cores.

The Proyecto Costa Escondida ("The hidden coast project", PCE), within which this study is part of, was created with the aim to better understand human coastal adaption at the site. Towards this end, the project is interested in determining the resources and facilities that existed at the site and how they changed over time. The sedimentological work presented in this paper will provide the knowledge needed to reconstruct the shoreline at the site in different time periods, thereby linking the natural framework to the archeological history of the site, producing a better understanding of human response to coastal change. One of the most outstanding features of Vista Alegre is that after its abandonment around the 16th century, it was unoccupied and left largely untouched until the present with the exception of a nearby rancho (Xuxub) that was occupied in the 19th century and some small-scale farming on the site in the middle of the 20th century. Therefore, the potential for preserved, undisturbed and pristine finds, possibly anthropogenic, is high.

2. Regional setting

Vista Alegre is located on the northeastern tip of the Yucatan Peninsula, in the state of Quintana-Roo, Mexico (Fig. 1). The Yucatan Peninsula is a low-relief carbonate platform, with a large freshwater aquifer (Beddows, 2004, 2003). The annual seasons are divided into the dry season from November to April, and a wet season from May to October. The average rainfall at the site is ~1000 mm/yr. The low topography combined with apparently stable tectonics over the past 125,000 years (Szabo et al., 1978), makes the northeastern coast of the Yucatan Peninsula an ideal study area to learn about human adaptation to changing coastal environments. The site is located 7 km east of the modern village Chiquilá, and 50 km northwest of Cancun. Vista Alegre is bounded to the north by Holbox Lagoon and Holbox Island, a large barrier island complex spanning over 50 km at the divide between the Gulf of Mexico and the Caribbean Sea. The area around Vista Alegre is a patchwork of mangrove islands, tidal flats, hyper-saline ponds, flooded forest and narrow channels (Fig. 1). Water salinities throughout the site are highly variable (freshwater to hypersaline) and sensitive to seasonal effects (Beddows et al., 2016).

Brady (1972) describes the sediments in Holbox Lagoon (Fig. 1). The results show that the lagoon sediments vary in the northern and southern areas due to a dominant easterly flowing current that may create a clockwise circulation pattern. The sediment of northern Holbox lagoon is composed of coarser-size sands transported from the open water into the lagoon. The southern area is characterized by finer sands combined with clay to silt-size muds. These finer sediments are composed mainly of foraminifera and algae combined with calcite muds that precipitated in the presence of fresh water (Brady, 1972).

Regional Caribbean sea-level studies show a sea-level rise of ~1.5 m over the last 3000 years (Khan et al., 2017; Milne et al., 2005; Toscano and Macintyre, 2003). Previous studies from the Caribbean region, like those from across the globe (Anzidei et al., 2014) demonstrate that sea-level rise varies from site-to-site, according to tectonics, isostasy, eustatic factors, etc. This emphasizes the need for localized studies to better understand the effect of sea-level rise on specific coastal communities (Cooper and Peros, 2010). The environmental setting combined with the archaeological history of Vista Alegre provide an especially rich data set (natural and anthropogenic) from which to study coastal change during and after the Maya period.

3. Methods

In 2011, six cores were collected from the bays flanking Vista Alegre on the east and west and the nearby shallow hyper-saline pond, referred to during the study as the 'Dead Zone' (Fig. 1), together with several samples from the sediment-water interface. A manual hammering push core system was manufactured locally which pounded PVC pipes into the sediments. Once hammered in, the cores were packed, capped, and attached to simple ratcheting tie-down straps for removal. The limit of penetration was always based on contact with a solid surface that prevented further penetration, which probably represents the bedrock. Maximum core length was 165 cm. All cores were collected from shallow depths (max 1 m water depth, minimum 30 cm). For the cores from the relatively deeper areas, a coring platform was attached to two small boats, and for the shallower water cores a platform was constructed from a pallet with 20 L water bottles for support.

Cores 1 and 2 were taken from the East Bay, a semi-closed terminal bay that has a single opening facing northwest (Fig. 1). Cores 3, 4, 5 were taken from the West Bay. The main inlet of the West Bay is a small channel opening to the northeast, there is another small narrow channel inlet in the southwest corner. Both channels may flow in and out of the bay, with alternative flow directions observed during the field campaign depending on tidal conditions. Core 9 was taken from a closed shallow (<30 cm) area with dead mangroves (the 'Dead Zone'), that appears to have very limited connection to other environments. A connection to other environments does seem to occur only during the high tides, and high sea-levels driven by strong northern winds. The at least partial (and possibly complete) isolation of the Dead Zone, combined with shallow depth makes the area highly sensitive to the weather conditions, and allows the water to reach hypersaline conditions during the dry season. All the cores were opened in the field, described, photographed, and sampled at one centimeter resolution except where not possible due to inclusions greater than 1 cm in size.

All the samples were analyzed for loss on ignition (LOI), and grain size. LOI was analyzed on bulk sediment, while grain size was analyzed for <2mm grains. For LOI, the protocols of Heiri et al. (2001) and Santisteban et al. (2004) were followed with a minor change of prolonging the burn times to 4 hours for both the 550c and 950c combustions. Interpretation of estimated organic content was based on the mass of the sample lost when combusted at 550 °C (LOI_{550}). A further mass loss at 950 °C (LOI_{950}) quantifies the thermal decomposition of carbonate in the sample, which is often associated with the presence of carbonate-shelled marine fauna in marine environments.

Grain size samples were subsampled at the same depth resolution as the LOI samples. The organic matter was removed from the samples adding 30% hydrogen peroxide a few drops at a time until no reaction was visually noticed. The samples were then stirred and sonicated for 15 minutes in distilled water, then poured into the Beckman 320 LDS particle size analyzer set to measure the volumetric (%) distribution of grain size from 0.01706 µm to 2000 µm. The results of the grain size analysis are received as total grain size distribution, which contains the whole range measured. The statistical values, mean, mode and standard deviation (S.D), were calculated from the total grain size distribution results. Terminology for grain size descriptions (e.g. fine sand, medium sand, coarse sand, etc.) follow Udden-Wentworth standards (Boggs, 2011; Wentworth, 1922). Outlier grain size and LOI values were reanalyzed and compared to descriptions and raw sample material to ensure their validity.

Based on the results of the LOI, grain size, and lithological descriptions, representative samples were chosen from each depositional horizon for foraminifera picking and radiocarbon dating. The foraminifera picking was done after wet sieving of the >150 µm portion, with a sample size of 1.25 cc (results normalized to 1 cc). Each picked sample was inspected to check if splitting was desirable. Samples that were split were picked to a total of at least 300 foraminifera (modified FOBIMO protocol, Schönfeld et al., 2012). In samples that had fewer than 300 individuals, the whole sample was picked to the maximum available population of foraminifera for that 1.25 cc sample. Individuals were categorized into rotalid, miliolid, or texturalia groups.

Radiocarbon dating was done mainly on carbonate-walled marine fauna (foraminifera and gastropods), and where no marine fauna was available bulk sediment and charcoal was dated. The samples were dated at DirectAMS lab, and calibrated using Calib 7.1 program (Stuiver et al., 2017). Estimated average accumulative sedimentation rates for each core were calculated based on the age value from the lowest measured sample to the top of the core (presumed modern surface, 0 cm).

4. Results

4.1 East Bay:

Core 1 (71 cm length, 0 cm compaction) was taken from 70 cm water depth (Fig. 1), with a core length average sedimentation rate of 0.1 mm/yr. Core 1 LOI_{550} values ranged from 21.4% to 50.8%. The bottom and top of the core showed typical values of ~30% with a notable spike defined by 3 points from the maximum at ~50 cm core depth. The LOI_{950} ranged from 11.9% to 37.8%, with typical values of ~20% but increasing step wise to 30% at 55 cm core depth. There was a single outlier value at 32 cm in the core that was confirmed by repeat analysis (Fig. 2). Total distribution grain size analysis for Core 1 showed mean values were between 12 to 400 µm, and S.D. values ranged from 11.9 to 475.6 µm (Fig. 2). Grain size analysis for Core 1 showed total grain size distribution was between fine silt to coarse sand at the bottom, while the upper part of the core had larger size values, reaching up to very coarse sand. Of the six samples analyzed for foraminifera, the dominant sub-order was represented by rotalids and the general abundance was low (under 57 per 1 cc), with a maximum of nearly 600 individuals per 1 cc at ~40 cm core depth, which was just above the spike in LOI_{550} and the step wise increase in LOI_{950} (Fig. 2). Two main distinctive horizons were defined based on the combined results. (see discussion below).

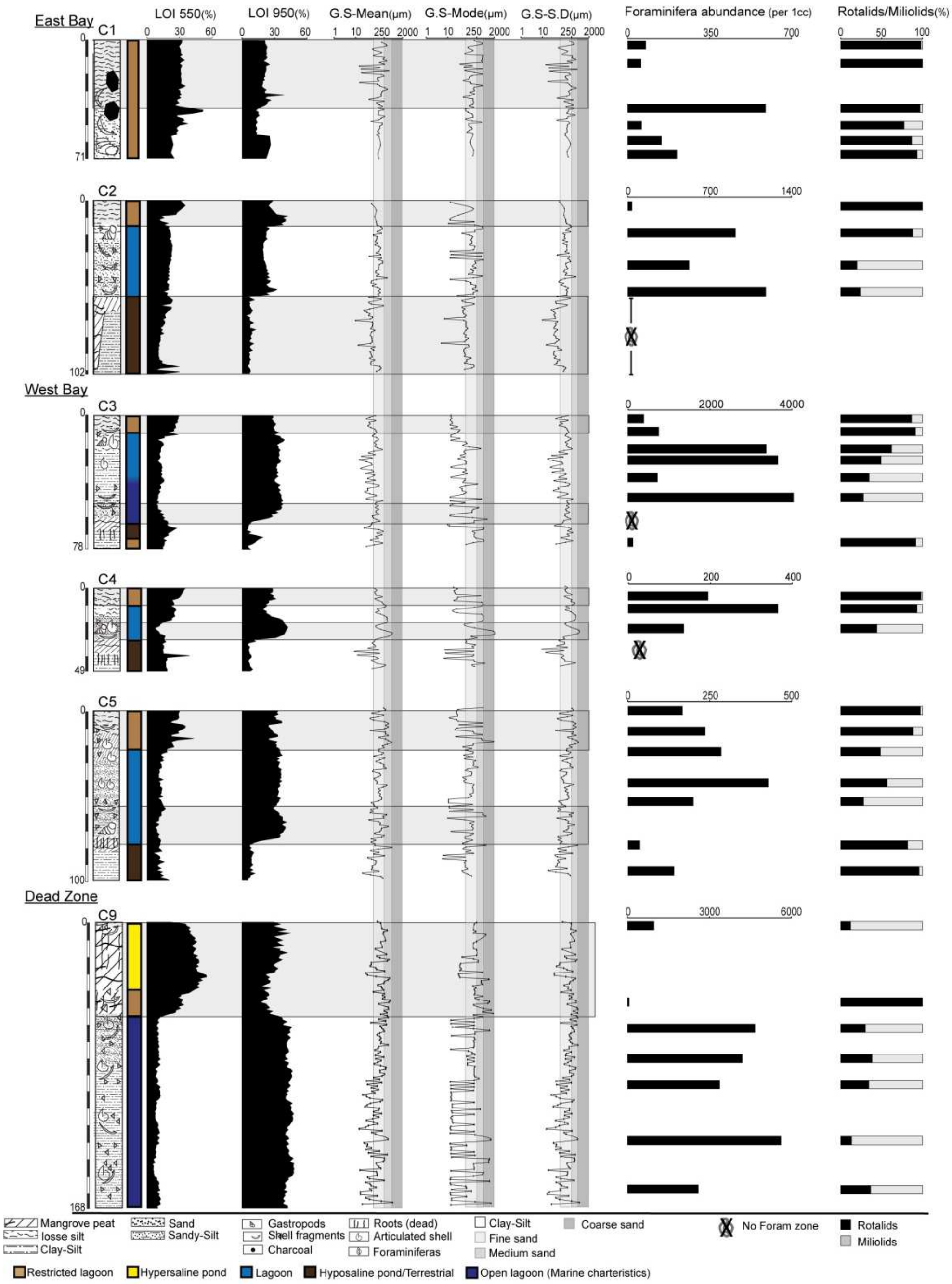

Fig. 2. Results from sediment core analysis. Note that the foraminifera abundance scale varies per core.

Core 2 (104 cm length, 8 cm compaction) was taken from 68 cm water depth (Fig. 1), with an average sedimentation rate of 0.035 mm/yr till depth of 55 cm (deepest point dated). LOI_{550} and LOI_{950}

values were measured between 7.7% to 34.8%, and from 2.8% to 36% respectively (Fig. 2). We observed several step-wise shifts in the LOI_{950} values, between which values were relatively stable. Mean grain size for Core 2 ranged between 7 to 319 µm µm, with S.D. values from 8.8 to 427.8 µm (Fig. 2). Grain size total distribution analysis for Core 2, showed the bottom half was of fine silt size grains, with several exclusions of fine sand at bottom, while the upper half reaches coarse sand values. In general, grain size varied between fine silt to coarse sand, with a few exclusions reaching very coarse sand fraction. Foraminifera ratios shift from the sub-order miliolid being the dominant foraminifera at the second third of the core to rotalids dominating the assemblage in the core's upper third. The total foraminifera population ranges from 256 to 1132 individuals per 1 cc where present, while lowermost portion of the core is foraminfera barren. Three horizons were distinguished based on the results.

Three samples were radiocarbon dated from Core 1, and two from Core 2, in the East bay (Table 1). The oldest result for the East Bay is 1571 ± 40 cal. yr B.P, from the middle of Core 2 (Table 1), and one sample at the top of Core 1 resulted invalid. The lowest section of Core 2 has an intrusion of fine muddy sediments into a sandy silt horizon with a sharp vertical contact, however no date is available for the horizon.

Table 1. Radiocarbon dating results

Sample Code	Material	Depth (cm)	d^{13}C (‰)	Radiocarbon age (yr B.P.)	1σ error (yr)	Calendar age (yr B.P.)
VA11-C01-020	Foraminifera	20	-9.6	395	28	I/A
VA11-C01-040	Foraminifera	40	-9.4	799	23	449±25
VA11-C01-071	Foraminifera	71	-6.0	1179	27	712±32
VA11-C02-013	Foraminifera	13	-19.1	770	26	400±76
VA11-C02-055	Foraminifera	55	-0.9	2014	27	1571±40
VA11-C03-010	Foraminifera	10	-2.2	874	26	492±41
VA11-C03-032	Shell	32	-5.0	1604	26	1180±41
VA11-C03-043	Foraminifera	43	-10.2	1749	26	1300±55
VA11-C03-061	Shell	61	-3.9	2110	28	1680±53
VA11-C03-074	Foraminifera	75	-5.0	3450	28	3320±89
VA11-C04-006	Foraminifera	6	-6.6	786	36	438±41
VA11-C04-017	Foraminifera	17	-4.4	1381	23	927±25
VA11-C04-02426	Foraminifera	26	-7.0	1250	23	745±43
VA11-C04-02830	Foraminifera	30	-5.6	1977	27	1540±40
VA11-C05-015	Charcoal	15	-32.2	312	24	I/A
VA11-C05-028	Shell	28	0.5	1127	28	675±25
VA11-C05-043	Shell	43	0.2	1517	23	1080±45
VA11-C05-066	Shell	66	-3.7	2052	26	1625±46
VA11-C05-092	Sediment	92	-19.3	2591	27	2282±42
VA11-C05-099	Shell	99	2.9	905	27	511±19
VA11-C09-009	Sediment	9	-23.7	334	26	I/A
VA11-C09-018	Mangrove Peat	18	-24.5	554	25	211±37
VA11-C09-048	Mangrove Peat	48	-14.1	837	27	474±22
VA11-C09-063	Shell	63	-0.5	1274	24	824±43
VA11-C09-080	Shell	80	7.4	1657	25	1228±28
VA11-C09-110	Shell	110	0.2	2002	26	1561±37
VA11-C09-135	Shell	135	-2.0	2443	26	2084±45
VA11-C09-162	Shell	162	-2.4	2809	25	2580±67
VA11-C09-164	Sediment	164	-30.3	1229	34	765±48

Table 1. Radiocarbon dating results

4.2 West Bay:

Core 3 (78 cm length, 5 cm compaction) was taken from 92 cm water depth (Fig. 1), with a core length average sedimentation rate of 0.022 mm/yr. LOI_{550} values range from 7.1% to 25.2%, and the LOI_{950} values are from 3.9% to 37.3% (Fig. 2). The middle third of the core has stable LOI values relative to the upper and lower third of the core. The mean grain size was measured between 15 to 244 µm, with S.D. values from 16.2 to 298 µm. The total grain size distribution ranged between fine silt to fine sand, with several samples reaching very coarse sand values. Foraminifera ratio values varied from rotalid dominance in the bottom and top of the core, while the central part is dominated by miliolids (Fig. 2). The total foraminifer population ranged from 116 to 3904 individuals per 1 cc, with the exception of between 61 cm to 69 cm, which had no marine fauna. Four horizons were differentiated based on all analyses.

Core 4 (49 cm length, 11 cm compaction) was taken from 83 cm water depth (Fig. 1), with an average sedimentation rate of 0.019 mm/yr at 30 cm depth (deepest point dated). LOI_{550} values ranged from 6.2% to 34% and LOI_{950} ranged from 4% to 36.8% (Fig. 2). The LOI values were quite stable at the top and the bottom of the core with a hyperbolic shape in the middle. Mean grain size values ranged from 7 to 580 µm, while S.D. values were from 7 to 608 µm. Grain size total distribution was concentrated in the fine silt to fine sand fraction, with several exceptions in the lower third of the core, reaching coarse sand values. Marine fauna were not present from 28 cm depth to the bottom of the core, the foraminifera ratio shifted between rotalid to miliolid dominance in the upper (0-28cm) portion of the core (Fig. 2). The total foraminifera population varied from 121 to 360 individuals per 1 cc. Four horizons were defined based on the results

Core 5 (101 cm length, 9 cm compaction) was taken from 85 cm water depth (Fig. 1), with a core length average sedimentation rate of 0.04 mm/yr. LOI_{550} values for Core 5 varied from 4.9% to 28.9% and the LOI_{950} values from 4.4% to 36.7% (Fig. 2). The LOI trend was stable in the middle of the core while top and bottom fluctuated. Grain size values ranged from 14 to 415 µm, with S.D. values between 15 to 525 µm. Grain size total distribution was between fine silt to fine sand, except from a few exclusions mainly in the upper quarter where grains reached vary coarse sand values (Fig. 2). Foraminifera ratio varied from dominance of rotalids in the top and bottom while miliolids dominated the middle part of the core. The general foraminifera population was between 35 to 360 individuals per 1 cc. Four horizons were differentiated based on the results of analysis.

Five samples were radiocarbon dated from Core 3, four samples from Core 4, and six samples from Core 5, in the West Bay cores (Table 1). The oldest ages for the cores was 3319 ± 89 cal. yr B.P., at the bottom of Core 3. One result was invalid at the top of Core 5. Two age reversals were present, at the middle of Core 4, and at the bottom of Core 5. At the bottom of Core 5 the reversal is probably a consequence of the core extraction, while at Core 4 the reversal is probably due to a sediment disturbance.

4.3 Dead Zone:

Core 9 (165 cm length, 0 cm compaction) was taken from 29 cm water depth (Fig. 1), with a core length average sedimentation rate of 0.062 mm/yr. LOI_{550} values varied from 4.4% to 54.7% and LOI_{950} from 12.9% to 38.4% (Fig. 2). From 60 cm depth in the core until the bottom the LOI values were quite stable (LOI_{550} ~7-12%, LOI950 ~30-38%), while from 0-60 cm values fluctuated from LOI_{550} ~10-55% and LOI_{950} ~36-13%. The grain size mean values ranged from 13 to 619 µm, with S.D. values from 17 to 572 µm. Grain size total distribution varied between fine silt to fine sand in the core, with several distinct samples reaching coarse and very coarse sand values. Foraminifera ratio was mostly in favor of miliolids except from one sample in which rotalids dominated. Total foraminifera population varies from 50 to 4646 individuals per 1 cc, where higher values (above 1000) are restricted to 60 cm and below in the core. Two main horizons were distinguished within the core.

Nine samples from Core 9 collected within the Dead Zone were radiocarbon dated. The oldest age was 2578 ± 67.5 cal. yr B.P (Table 1). One sample resulted invalid at the top of the core.

5. Discussion

All of the cores, regardless of length, contained at least two distinctive horizons, and in some cases up to four. Based on the combined results of all the analytical methods, ages, and stratigraphy, the identified horizons were clustered into main environmental facies, which generally correlated with horizon boundaries (Fig. 3). These facies were used to determine the sequence of sea-level change in the sites micro environment, for the East and West Bays and the Dead Zone. According to the results, a general trend of sea-level rise changed the landscape, in some cases significantly, in the past three thousand years. A hypothesized reconstruction, showing a suggestion of facies changes in the water bodies due to sea-level change, was made according to the results (Fig. 4).

In general, the sequence of changes interpreted in the West and East bay begin with a restricted pond or terrestrial area, which turns into a lagoon, and finally transitions into the restricted lagoon present today. The dead zone had a different sequence, first represented by a marine-like lagoon followed by a transition into the present hypersaline, very restricted water body.

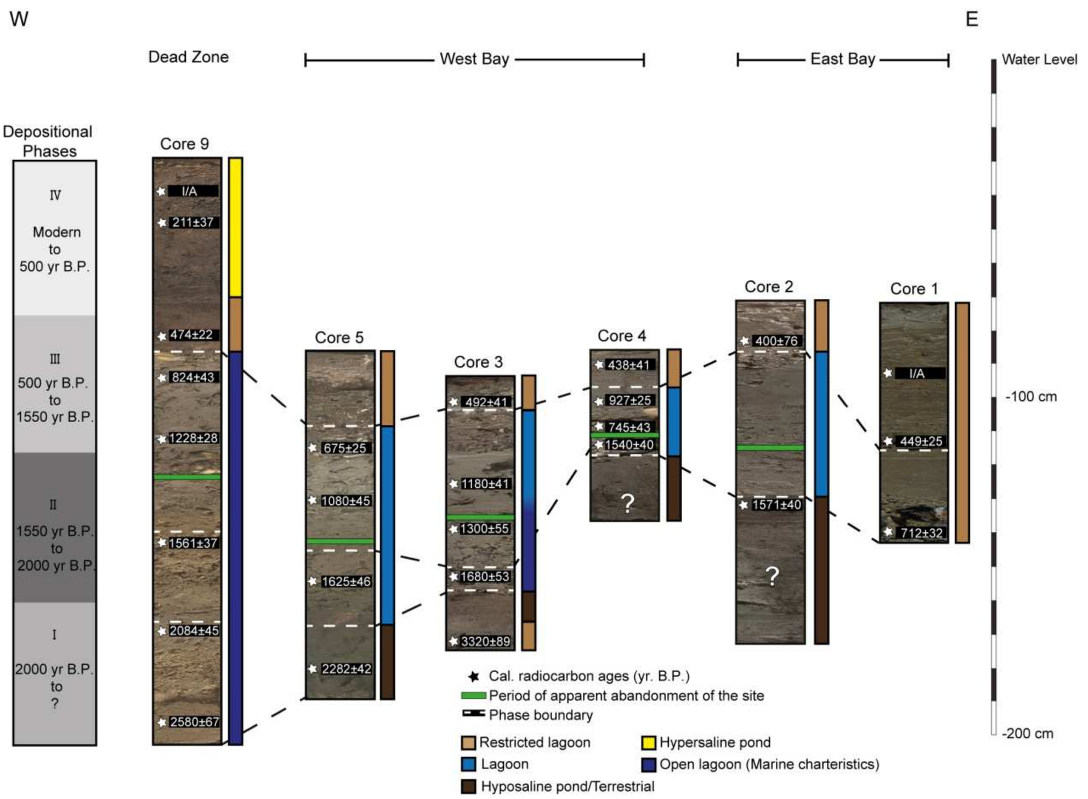

Fig. 3. Core correlation. Calibrated radiocarbon ages are marked in the point taken from the core with a star. The across-site correlation was determined by combining the sedimentological results and ages.

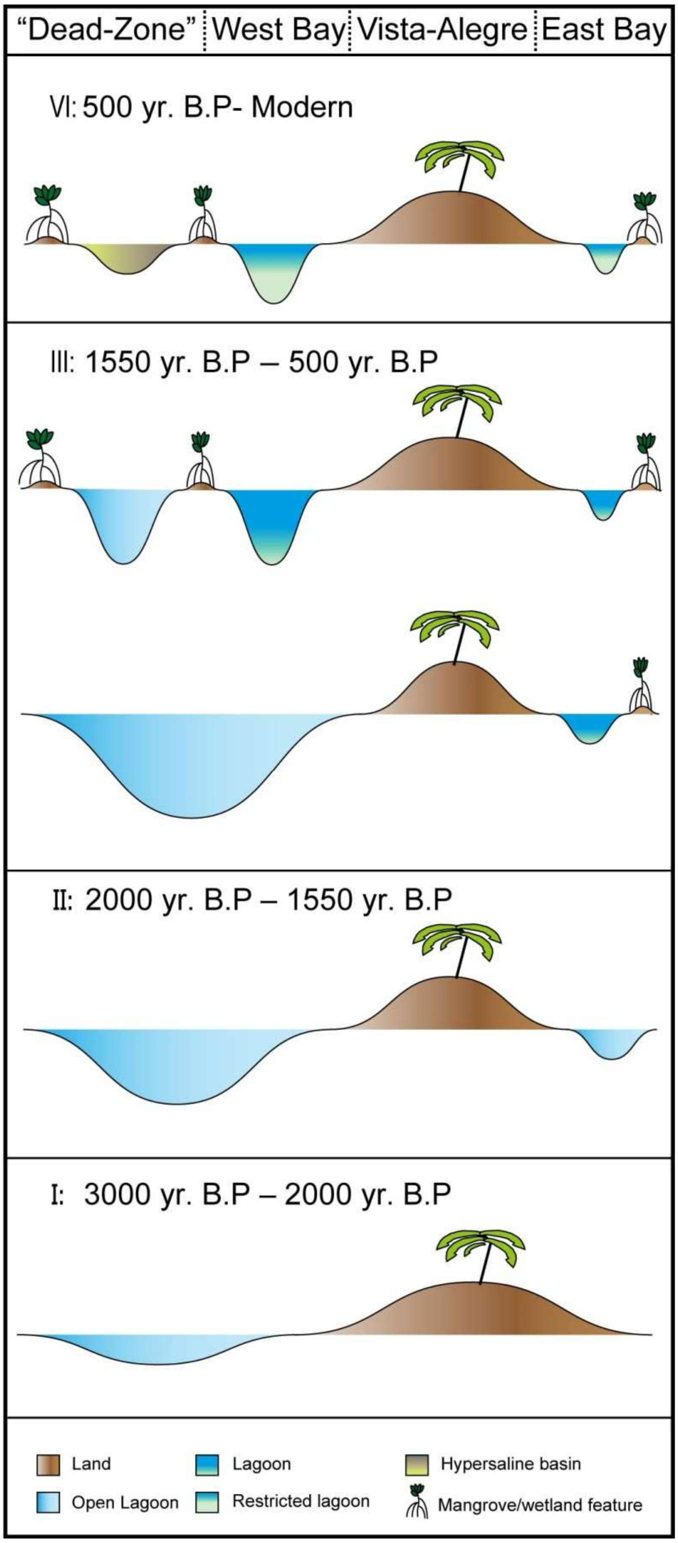

Fig. 4. Hypothesized environmental sequence. Illustration of possible coastal changes due to sea-level change, based on coring results.

5.1 East Bay:

According to the results from the lowest horizon of core 2, the East Bay was terrestrial or a very restricted, possibly hypo-saline, enclosed pond - until 1550 yr B.P. This is supported both by the absence of foraminifera and the low LOI_{950} values in this horizon. By 1550 yr B.P, an event transitioned it to a flooded area. The flooding may have occurred relatively rapidly, as the changes in values are abrupt in Core 2 at 59cm depth. For example, LOI_{950} values shift rapidly from values under 10% to values above 20%, and in tandem, the first evidence of marine fauna appear with no signs of a gradual transition, reaching the highest values of individuals per 1 cc in this core immediately following this transition (Fig. 2). Also, the grain size values in this horizon shift from finer to coarser mean values, probably due to the introduction of marine fauna to the sediment, which also increases the S.D. values, reflecting more poorly sorted sediments. Once present, the foraminifera population is dominated by miliolids with a total population exceeding 1000 per 1 cc, indicating a different marine environment than at present, with characteristics more like a lagoon area with typical marine salinity values, with conditions supporting a wider range (higher diversity) of foraminifera species.

In the more recent sediments of the East Bay (Phase IV, Cores 1 and 2) the total foraminifera population falls to less than 100 individuals per 1 cc, with dominance of rotalid taxa (>90%). The dominating rotalids are mainly from the *Elphidium* and *Ammonia* genus (Fig. 5). These species are known for their tolerance to a wide range of marine conditions, from brackish to hypersaline (Murray, 1971; Reddy and Jagadiswara Rao, 1984; Sen Gupta, 1999). Previous work on the modern condition of the site shows a wide range of water salinity values, varying between the wet and dry season (Beddows et al., 2016), from hypersaline to brackish water, only species with high tolerance to these changes will survive in these conditions.

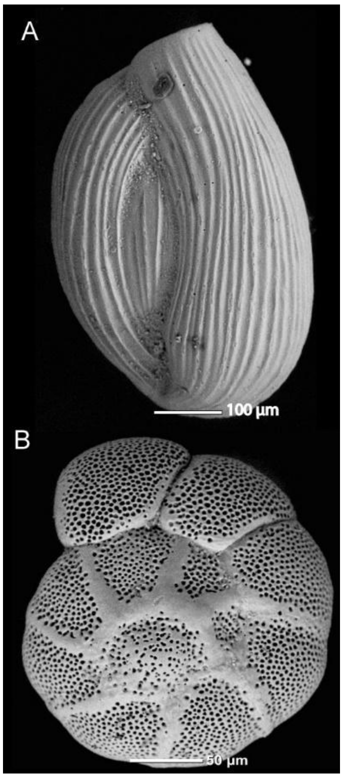

Fig. 5. Examples of representative foraminifera types. (A) Miliolid (*Quinqueloculina*) (B) Rotalid (*Ammonia*).

The East Bay cores revealed three distinctive environmental facies: terrestrial/hypo-saline pond- low LOI values and no marine fauna present; lagoon- high LOI values and high number of foraminifera individuals; restricted lagoon- low total foraminifera population dominated by rotalids, and muddy to sandy sediments, showing possible restriction changes, due to creation of barriers/mangrove lines. The sequence described in the East Bay can be interpreted as a shallowing upward sequence (James. 1977). This suggests that the sedimentation rate eventually outpaced sea-level rise rate, as might happen in carbonate mangrove environments (e.g., Parkinson, 1989). From the interpretation we found that Vista Alegre was probably a larger terrestrial site relative to today, prior to, and possibly even immediately after the flooding occurred at ~1550 yr B.P. How far the land extended is still uncertain, but adding only the East Bay flooded area as we know it today, will add approximately 15% to the exposed terrestrial surface area. The possibly larger terrestrial area, combined with a wider and easier to access East Bay, provided an opportunity for larger volumes of human maritime activity, compared to the present environmental conditions at the bay.

5.2 West Bay & Dead Zone:

The environmental setting as we know it today in the West Bay and the Dead Zone, appear to have remained stable for the last 500 years, similar to observations from the East Bay. Up until then, the area went through a series of changes with regard to the environmental fingerprints, probably affected by sea-level rise, in each of the areas cored (Fig. 4). Some of the changes are represented from core to core, while others appear to occur relatively independently. For example, Core 3 from the West Bay correlates environmentally with Core 9 in phases II and III, showing similar fauna rich sediments (Fig. 2), suggesting that these areas were connected in the same system at that time, or had similar characteristics. More broadly, the environmental characteristics in the lower part of Core 9 are very different than today, including rich marine fauna versus those present in the low-diversity, hyper-saline pond present today. This suggests that the Dead Zone was not a closed basin, but rather connected to Holbox Lagoon until phase III (Fig. 3 and Fig. 4), and that Core 3 was part of the same system. The foraminifera population in Core 9 reached 4600 individuals per 1 cc, at that time, with a slight dominance of miliolid species (>60%). This foraminifera ratio represents normal marine lagoons and carbonate platforms, different than the modern dominance of miliolids (88%) which is consistent with the current hypersaline conditions (Armstrong and Brasier, 2005; Sen Gupta, 1999).

At their bases Cores 3 and 5 are initially different than Core 4. In Phase I Core 4 seems to be terrestrial, while Cores 3 and 5 shows characteristics of a restricted lagoon/hypo-saline marine facies, as described in the East Bay. Core 3 initially has very few foraminifera, followed by a foraminifera-barren layer, returning to low abundance of foraminifera for the end of Phase I. Then, in Phase II, Cores 4 and 5 become more similar across all parameters, except for sedimentation rate. Phase II is interpreted as the shift to lagoon facies in the West Bay, similar to the lagoon facies described in the East Bay. The bottom of Phase II shows the change, and the top the stabilization of the feature, which covers most of Phase II time span. Core 3 at that time resembles the sediments in Core 9. Interestingly, the total foraminifera population in Core 3 is ten-fold higher compared to Cores 4 and 5 during this period of disassociation, and the grain size is smaller than in Cores 4 and 5. These observations suggest that the West Bay might have been divided into 2 smaller marine environments, such as a pool in Cores 4 and 5 area, that might had limited connection to Core 3 area. Meanwhile, Core 3 was connected to the same system as the more open (at that time), and probably deeper, Dead Zone and Holbox Lagoon.

The West Bay was inundated during Phase II, which is represented by chronologically similar markers in Cores 3 and 5; followed by a shift from terrestrial to marine characteristics in the more inland located Core 4 (Fig. 2 and 4). Similar to observations from the East Bay flooding event, this change occurred rapidly across proxies; LOI_{950} rises from ~5% to over 30% and grain size switches from very fine sand to coarse sand with poorer sorting. The timing for both the East and West Bay flooding appears to be relatively synchronous, suggesting a site-wide phenomenon the occurred in a few hundred years, between ~2000 yr. B.P to ~1550 yr B.P.

The environment of the Core 9 area ('Dead Zone') becomes unique and distinctive at the bottom of Phase IV, which corresponds to synchronous changes within Cores 3, 4, and 5. The foraminifera numbers are falling dramatically, with a dramatic increase in LOI_{550} values. These changes point on the turning of the area to the hyper-saline basin present today. The area was probably not enclosed at once, and apparently mangroves have been present in its area, accelerating the sedimentation, finally cutting it off the other marine systems around it.

Sea-level trend at the site is in agreement with regional studies from the area (Khan et al., 2017; Milne et al., 2005; Toscano and Macintyre, 2003), showing a general trend of sea-level rise. Also the time of significant facies changes at the site (flooding of both bays) around ~2000 to ~1550 yr B.P was identified in other areas in the Caribbean region as a possible pulse in sea-level rise (Leonard, 2013;

Peros et al. 2015; Wollwage et al., 2012). The Maya site of T'isil, located in the interior of the Yucatan Peninsula, was abandoned at ~1550 yr B.P (Wollwage et al., 2012), correlating with the abrupt flooding of the bays flanking Vista Alegre. The observed sea-level rise in Vista-Alegre area (if natural), could have affected the water table level for tens to hundreds of kilometers from the site (Beddows et al., 2016), and might be the reason, or amongst the reasons for the contemporaneous abandonment in the interior region in sites like T'isil. Previous work from other interior sites in the region, show the water table was about 85 cm lower than present in the Late Preclassic period, around 2000 yr B.P (Leonard, 2013). The water table reached its current level around 950 yr B.P, revealing the rise was not linear, and might have had high-low fluctuations and abrupt changes (Leonard, 2013; Wollwage et al., 2012). These findings are synchronously occurring with the flooding of Vista Alegre bays, and might point towards sea-level rise as the primary flooding mechanism, also affecting the inner sites water table. Sea-level rise mechanism in Vista Alegre is not fully understood yet, and in addition the archeological history of the site might be related to changes in water levels in the East and West Bays as well (discussed in section 5.3).

5.3 Archaeological Comparison to Environmental Phases:

As observed in the suggested reconstruction of the environmental facies (Fig. 3 and 4), the changes in the landscape are more complicated than moving the modern shore seaward or landward. This, for example, can be observed in the present day Dead-Zone, which was once a deeper marine feature, more similar to present day Holbox Lagoon. The micro-environmental changes are of great importance at this site. They also are informative when compared to the understanding of the human activities during these same periods and makes it possible to produce a more comprehensive time sequence incorporating natural and anthropogenic factors.

During Phase I, the exposed terrestrial area of the site was at its largest extent during the period of human habitation. The earliest ages in the cores are about 3200 yr. B.P., and the first evidence for human activity begins around 2750/2650 yr B.P. (Glover et al., 2011b). The people who were there would have found a peninsula with open access to Holbox Lagoon, and most likely well-vegetated terrain. By 1850-1650 yr B.P (environmental Phase II), the site had a robust population and possibly reached its largest extent based on the relative abundance of ceramic materials recovered from excavations. Simultaneously, Phase II, environmentally, shows the flooding of the site and areas that were terrestrial are now inundated (see Cores 2 and 4), producing more opportunities for approaching the site from the water. The bays were relatively deeper in the earlier years of Vista Alegre occupation, as shown by the miliolids' dominance in the foraminifera population, compared to the modern shallow and more weather-sensitive conditions, resulting in a wider range of water conditions dominated by rotalids. According to archaeological evidence at the site and nearby, at the time period of the East and West bays inundation (~2000-1550 yr. B.P.), the site was flourishing and trading with settlements both in the nearby inland region and farther away (Glover et al., 2011b).

The question that arises from these results is the following. Was this a natural rapid flooding or a manmade expansion of the marine area around the site, or a combination of the two? At present, the precise mechanism cannot be unequivocally determined. The changes in regional water table levels (discussed in section 5.2) might point towards a regional sea-level change, resulting in a natural flooding of the bays. It should also be considered that the proxies point towards a relatively abrupt event, suited to short term events such as intense hurricane or tsunami, which can change the landscape dramatically in a short time period, although the evidence is not unequivocal. Curiously this flooding is happening during the time when the population of Vista Alegre remains active relative to the contemporaneous sites in the interior (Fedick, 2014; Glover, 2012, 2006; Leonard, 2013). Studies of harbor development in the Mediterranean suggest an overall maritime harbor sequence of exploitation of natural protected coastal features along the shoreline for the use of harbors, followed by reinforcing natural features and building seaward from the coastline (sometimes referred to as 'proto-harbors'), and eventually evolving into full-blown artificial ports and harbors (Morhange and Marriner, 2010). One possibility is that the change to a deeper lagoon feature was related to dredging the bay or other manipulation of the landscape, to ease marine transit and control the environmental setting. This could have been in the form of maintaining or improving access by preventing overgrowth, clearing rubble or other obstacles, or otherwise manipulating the landscape. Whether this pulse was natural or anthropogenic, it probably made the West Bay accessible directly from the Holbox Lagoon, offering a much bigger maritime transit area, and allowing in tandem an easier access to the East Bay.

The current thinking on seagoing dugout canoes is based on the ethnohistoric record. These canoes were made of large, tropical hardwood trees and had room for over 20 paddlers along with the cargo and even a shaded platform for high status individuals (Leshikar, 1996; Thompson, 1949). While it is entirely possible that these same large dugouts have a much longer history in the Maya area, the frequency of coastal, long-distance trade certainly increased in the Terminal Classic period, associated with Chichén Iztá's rise to power (e.g., Andrews, 1978; Braswell, 2010; Cobos, 2004; Glover et al., n.p., Kowalski and Kristan-Graham, 2007; Robles Castellanos and Andrews, 1986). These are the canoes that would have been arriving at Vista Alegre seeking provisions (water and food), and a place to trade and rest. Most coastal sites in the Maya area are small in aerial extent (see Andrews, 1990 and Clark, 2015: Appendix A for recent overview of coastal sites in the Maya area), however temporary structures could have easily been constructed to allow these traders a place to swing a hammock for the night. With the island stripped of most of its vegetation, the pyramid would have been visible from a long distance. As the canoes arrived, the shoreline would have most likely had a number of perishable structures as well as larger stone platforms near the water's edge. Along with hosting visiting traders, the inhabitants of Vista Alegre would have been fishing (or mending nets), collecting shellfish like conch and other gastropods from the shallow waters of Holbox Lagoon, or weaving cotton thread, as evidenced by the spindle whorls recovered at the site, among other activities (Glover and Rissolo, 2010). Life on the island changed as Chichen Itzá's power waned and perhaps new trade alliances were negotiated (Glover et al., 2011a).

Around 1250 cal. yr B.P. an apparent 100 yr abandonment occurs (Glover et al., 2011b). This coincides with the early natural phase III (Fig. 3). At that time the East Bay shows no change in any parameters, but on the other hand we observe a small sedimentological signature for this event in the West Bay. Cores 3 and 5 show a decrease in shell content in the sediments (slightly lower LOI_{950} values) before this event, with an even lower value marking the timing of the abandonment itself. Foraminifera numbers also fall in this time period and return afterwards. Overall, these could be indications of generally lower marine productivity or some sort of systemic change that is impacting the site more broadly. There is a slight increase in the organic component (higher LOI_{550} values) for a short time, which could be related to increased development of secondary vegetation grown in the absence of people, modern observations show how quick the vegetation overtakes barren spots at Vista Alegre. Previous studies show that the northeast Yucatan suffered from a drought in that time period (Curtis et al., 1996), while more central and northwestern areas of the Maya area were having a humid rainy period (Hodell et al., 1995; Medina-Elizalde et al., 2010). It is unclear yet if any of those climate phenomena affected Vista Alegre at that time, but the environmental markers are supporting the idea that human activity was reduced during that time at the site.

The upper half of Phase III is marked on the landscape by the continued connection from the West Bay side of the site to the lagoon, though Cores 9 and 3 have signs of even more diversity and open-water foraminifera; but a trend towards a more restrictive environment begins in the East Bay. The archaeological remains suggest a repopulation after the apparent abandonment, with evidence that connects the site to Chichen Itzá, and long distance trade, which would have been supported by seagoing dugout canoes laden with goods from across Mesoamerica.

The connection between Phase III and IV, represents the timing of shift from lagoon like facies, to restricted lagoon facies. This period of gradual change, relates to a time in the archeological history of Vista Alegre (post-Chichen Itzá) when the site was functioning less as an interregional trade hub with a permanent settlement and more as a small, coastal site, possibly visited as a pilgrimage locale (Glover et al., 2011b). The reduced usage of the site, combined with the bay's geographical setting may have resulted in the infilling of those site-flanking bays, similar to what has happened in other harbor sites worldwide when no dredging or interference occurred. Vegetation would have been left to grow unabated, leaving the gradual change signature. This apparent infill, accelerated by untouched mangrove sediment traps (Scoffin, 1970), will cause a more stressed marine environment, more sensitive to changes, with a wider range of physical parameters such as salinity, pH and water temperature like those observed at present (Beddows et al., 2016), with lower abundance and dominance by rotalids- mainly *Ammonia*, known to have a wider environmental tolerance.

Phase IV represents the final environmental period of the site. During this phase, Core 9 is a high salinity, shallow, extremely restricted area while the East and West Bays are connected to the more open lagoon through narrow channels, resulting in higher-than marine salinities at times, but lower than the Dead Zone. During the wet season the bays can reach sub-marine salinity values, but still not potable values. Historically, the site is known to have had its last human activities in the sixteenth century AD. The site is left untouched at that time, and the natural forces are solely controlling the environmental factors, infilling the bays, making them the restricted flooded landscape we observe at present.

6. Conclusions

Sea-level rise has caused changes in the marine environmental facies at the maritime Maya site of Vista Alegre, during the past 3000 years. This results in a modern site layout that is apparently quite different from the one encountered by its ancient inhabitants. The changes in the shorelines throughout time have created the complex modern site setting witnessed today. The creation of specific features, such as the "Dead Zone" could not be determined by relying solely on the regional sea-level curves and modern surface topography. Rather, it required site-scale coring, which exposed the underlying sequences that were not apparent from the surface. The cores, with a few tens of meters location difference, do not show perfect correlation, and in some cases vary considerably. This highlights the complex nature of the mangrove marsh environment combined with the anthropogenic footprint of resource usage preserved in the sediment. The main features of interest for marine activity at present in the modern landscape are the East and West bay, together with the shallow Dead Zone. In this study we show that those bays were deeper than at present at the time the site was inhabited, making those areas more suitable for maritime activity. The then deeper bays, together with the direct connection from the open area into what is today called the 'Dead Zone', reveals a larger area available for maritime activity at the past. This reveals the high potential of Vista Alegre as a more prominent harboring location, offering an easy access of incoming canoes into the site.

Four main phases, and facies, were defined from these cores, some of them correlating to archaeological periods on site. While we cannot unequivocally differentiate between the natural versus anthropogenic signatures in all of the sediments, there are some cases such as the final abandonment of the site where we can presume that the infilling observed in the bays is a natural post-abandonment occurrence. The multi-proxy approach undertaken in this work allows us to better differentiate between environments, events, and landscapes; which contributes to our more holistic understanding of the environment with which the maritime Maya interacted. Based on these results, it will also be possible to better direct any future excavation or survey efforts aimed at exposing or excavating Maritime Maya coastal features.

Worldwide, submerged landscapes contain the remains of a large portion of human cultural heritage. Trade, migration, innovation, and other aspects of human development occurred in these environmental zones and contain a record of both environmental and human history. As a result of the study presented here, we now have a new understanding of how sea-level varied at Vista Alegre during Maya occupation, and have a baseline for approaching significant archaeological and anthropological questions.

Acknowledgments

Funding for the study was provided by NOAA (NA110AR0110050), Norman Krischer, and Sir Mick Davis. The authors appreciate the assistance provided by M. Kanari, E. Shemesh, Y. Braun, N. Taha, MGM lab group, secretaries of Charney School, the people of Chiquilá and Kantunlikin, Wes Peterson, Dan Leonard, Frida and Diego. We also thank the Consejo de Arqueología of Mexico's National Institute of Anthropology and History (INAH), and Adriana Velazquez Morlet and the members of the Proyecto Costa Escondido at large. The authors would also like to thank the anonymous reviewers for their thoughtful comments.

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