Late Holocene sea-level rise in Tampa Bay: Integrated reconstruction using biomarkers, pollen, organic-walled dinoflagellate cysts, and diatoms

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ABSTRACT

A suite of organic geochemical, micropaleontological and palynological proxies was applied to sediments from Southwest Florida, to study the Holocene environmental changes associated with sea-level rise. Sediments were recovered from Hillsborough Bay, part of Tampa Bay, and studied using biomarkers, pollen, organic-walled dinoflagellate cysts and diatoms. Analyses show that the site flooded around 7.5 ka as a consequence of Holocene transgression, progressively turning a fresh/brackish marl-marsh into a shallow, restricted marine environment. Immediately after the marine transgression started, limited water circulation and high amounts of runoff caused stratification of the water column. A shift in dinocysts and diatom assemblages to more marine species, increasing concentrations of marine biomarkers and a shift in the Diol Index indicate increasing salinity between 7.5 ka and the present, which is likely a consequence of progressing sea-level rise. Reconstructed sea surface temperatures for the past 4 kyrs are between 25 and 26 °C, and indicate stable temperatures during the Late Holocene. A sharp increase in sedimentation rate in the top ~50 cm of the core is attributed to human impact. The results are in agreement with parallel studies from the area, but this study further refines the environmental reconstructions having the advantage of simultaneously investigating changes in the terrestrial and marine environment.

1. Introduction

Holocene sea-level rise shaped the low lying Gulf Coast of Florida into its present day appearance. Sea-level studies for this region suggest a transgression over the past 10 kyrs, although there is a contrast between studies showing decelerating rates over the past 5000 years (Scholl et al., 1969; Törnqvist et al., 2004) and studies showing a Mid or Late Holocene sea-level highstand (Goodbred et al., 1998; Blum et al., 2001; Törnqvist et al., 2004). Detailed studies of the impact of Holocene sea-level rise can be used for improving our understanding of the environmental implications associated with the modern and forecasted sea-level rise. Multi-proxy studies are a valuable tool for paleo-environmental reconstructions especially when they combine marine and terrestrial environmental information.

Pollen provides a valuable proxy for environmental reconstructions because of its good preservation, abundant presence in most terrestrial and marine sediments and its sensitivity to changes in southwest Florida's hydrological cycle (Donders et al., 2005; Willard et al., 2007). Pollen abundances reflect regional vegetation development and, in marine records, also record variations in runoff rates. Nearby coastal vegetation can further influence the signal (Donders et al., 2008). Facies changes as a result of sea-level fluctuations can also affect the pollen signal by altering the depositional setting, as is evident in the late-Glacial from the southwestern Florida Tampa Bay record (Willard et al., 2007).

Diatoms and dinoflagellates thrive in offshore waters and their remains (e.g. diatom frustules and organic-walled dinoflagellate cysts, or dinocysts) have been found in surface sediments of Florida

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shallow marine environments such as Rookery Bay (Cremer et al., 2007). Relative species distributions of these groups can be used to reconstruct amongst others: sea surface salinity, stratification and productivity (Laws, 1988; Marret and Zonneveld, 2003; Sangiorgi et al., 2006; Van der Meer et al., 2008).

Another valuable proxy for environmental reconstructions is biomarkers. These geochemical fossils are specific compounds, mostly lipids, which can be linked to their organic precursors and can preserve over long geological time scales (Killops and Killops, 2005). Biomarkers derive from plants and trees but also from microorganisms like dinoflagellates, diatoms, coccolithophore, and are therefore ideally suited to link the terrestrial and marine environment. Terrestrial biomarkers can provide information on changes in hydrology like increased runoff. Marine biomarkers are often used for the reconstruction of marine variables such as sea surface temperature (Prahl and Wakeham, 1987), salinity (Versteegh et al., 1997) and productivity (Sachs and Anderson, 2005). Hence, combining biomarkers with terrestrial and marine microfossil records makes the environmental reconstructions more robust.

One of the largest estuaries in southwest Florida is Tampa Bay, which consists of interconnected bays and lagoons with shallow water depth. In 2004 a ~5 m continuous Holocene record was recovered from Hillsborough Bay, part of Tampa Bay (Cronin et al., 2007). A shift in sediment and microfossil content around 7 ka was interpreted as a transition from a lacustrine to an estuarine environment, as a consequence of post-glacial sea-level rise (Cronin et al., 2007). The rise in sea-level is estimated to be about 7.5–8 m over the last ~7 kyrs at this site (Cronin et al., 2007). Here we build upon the initial study by Cronin et al. (2007) applying a suite of organic geochemical and micropaleontological proxies to gain detailed environmental information from the terrestrial and the marine environment during Holocene sea-level rise.

2. Material and methods

2.1. Material

Hillsborough Bay core TB-04-VC-77 (Fig. 1) was collected in summer 2004, by the U.S. Geological Survey in cooperation with Eckerd College and the University of South Florida, with a vibracorer deployed from the R/V *Gilbert*. The core comprises 511 cm of sediments collected at a water depth of ~4 m in a 6 m long by 7.6 cm wide aluminium barrel. Based on the down core changes in sediment colour ten samples were selected and freeze–dried (Fig. 1). These samples were split for the different analytical techniques, allowing direct comparison of proxies and results. Depths are relative to the core top and reported in cm below sea floor (cmbsf).

2.2. Age model

The age model is constructed using two linearly interpolated radiocarbon dates (Cronin et al., 2007) and pollen biostratigraphical ages (Fig. 1). Radiocarbon ages are based on *Polygonum*-seeds (depth: 4.28 m, ^{14}C age: 8223 yr BP $\pm$ 50 yr), and *Mulinia* sp. shells (depth: 3.1–3.15m, ^{14}C age: 5441 yr BP $\pm$ 40 yr) and were calibrated using atmospheric and marine corrections (CALIB 5.0.2, http://calib.qub.ac.uk/calib/) (Cronin et al., 2007).

Casuarina (Australian pine) has its first occurrence between samples 93 and 39 cmbsf. It is an exotic plant introduced to the Florida peninsula around 1900 AD (Alexander and Crook, 1974), corresponding with a pollen-age of ~50 yr BP (i.e. before 1950). A strong expansion of *Pinus* between sample depths 352 and 329 cmbsf is dated between 7.2 and 4.4 ka based on regional correlation (Watts, 1969, 1971, 1975, 1980, Watts and Hansen, 1994). According to the age

model, the sediments represent approximately the last ~10 kyr, presuming deposition rates of 0.04 cm/yr to ~0.3 cm/yr based on this core and previous studies (Brooks, in press).

2.3. Biomarkers

Extracts were obtained from ca 1.5–6.5 g of freeze–dried and powdered sediments, using an ultrasonic homogenizer (Branson sonifier 250 Analog) and a solvent mixture of dichloromethane (DCM) and methanol (MeOH) (2:1 v/v). Samples were ultrasonically stirred 5 times for 3 min. Resulting extracts were combined and rotary-evaporated under near vacuum to remove solvents. Extracts were treated with activated copper to remove elemental sulfur. Traces of water were removed with sodium sulfate.

Quantification of compounds was performed on gas chromatograms of total lipid fractions (TLFs). Extracts were treated with diazomethane to convert fatty acids into methyl esters and with N.O-Bis(trimethylsilyl)trifluoroacetamide (BSTFA) to convert alcohols into trimethylsilyl (TMS) ethers.

Extracts were separated into three fractions of different polarity to enable identification of compounds with relative low concentrations. An aliquot of the total extracts (~80%) was separated over a column with activated aluminum oxide using solvent mixtures hexane:DCM (9:1 v/v), DCM and DCM:MeOH (1:1 v/v), resulting in, respectively, a fraction containing alkanes, alkenes and aromatics, a fraction containing aldehydes and ketones, and a fraction containing polar compounds.

Gas chromatography (GC) was performed using an HP Gas Chromatograph fitted with a CP-Sil 5CB fused silica capillary column (30 m × 0.32 mm i.d.) and a flame ionization detector (FID). A flame photometric detector (FPD) was used to check for elemental and bound sulfur. Samples were injected on-column, with helium as carrier gas set at constant pressure (100 KPa). The oven was programmed starting at 70 °C, heating by 20 °C/min up to 130 °C, by 4 °C/min up to 320 °C and then kept at this temperature for 20 min. Mass spectrometry (GCMS) was performed using a ThermoFinnigan Trace GCMS with the same type of column and oven program as used for the GC. Compounds were identified using retention times and mass spectra. Quantification of compounds was performed by peak area integration in FID chromatograms relative to a standard (squalane) which was co-injected with TLF.

Total organic carbon (TOC) content of sediment samples was determined with a Fison Instrument NA 1500 NCS analyzer, on samples treated with HCl to remove inorganic carbon. The alkenone unsaturation index ($U^{K'}_{37}$) was calculated, based on the relative abundances of C_{37} alkenones with 2 or 3 double bonds (Prahl and Wakeham, 1987), which were present in the fraction containing aldehydes and ketones.

$$U^{K'}_{37} = [C37:2]/[C37:2+C37:3] \tag{1}$$

Sea surface temperatures were calculated using the global calibration of Müller et al. (1998).

$$U^{K'}_{37} = 0.033*T + 0.069 \tag{2}$$

A diol index (DI) was calculated based on relative abundances of C_{30}- and C_{32}- 1,15 diols (Versteegh et al., 1997), present in the TLF.

$$\text{Diol index} = 100*[C_{30}1, 15 \text{ diol}]/([C_{32}1, 15 \text{ diol}] \\ + [C_{30}1, 15 \text{ diol}]) \tag{3}$$

2.4. Palynology

Sediments for palynological analysis were dried, weighed, and treated following standard methodology (Wood et al., 1996). Prior
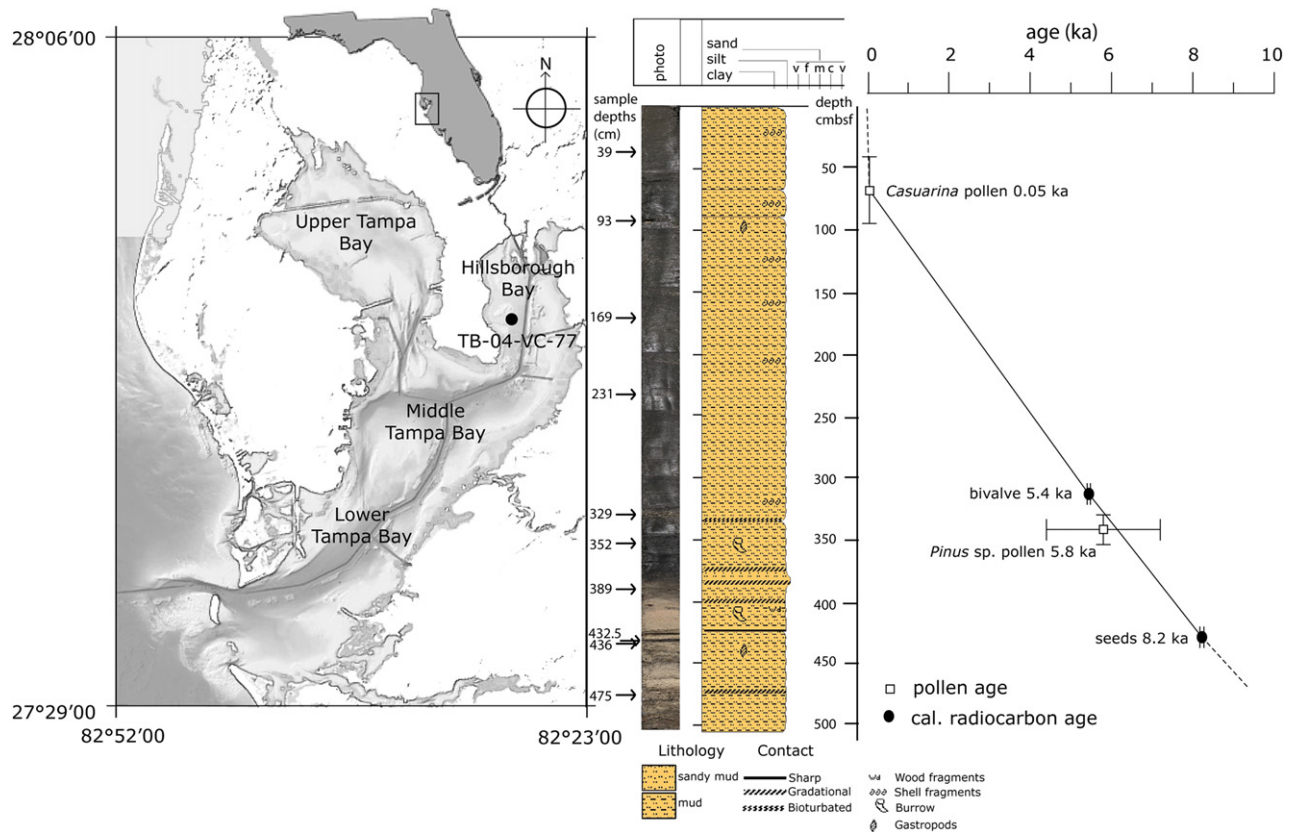
Fig. 1. On the left: map of Tampa Bay region and location of core TB-04-VC-77 (modified from Tyler et al., 2007). At the right: core photo and core log (modified from Cronin et al., 2007) and constructed age model.

to processing *Lycopodium clavatum* tablets with known amount of spores were added to the samples in order to be able to calculate concentration values. Treatment included the removal of carbonates with hydrogen chloride (HCl) (30%), and silicates with hydrogen fluoride (HF) (40%). Coarse and fine material was removed from the samples using sieves with a 250 μm and 10 μm mesh, respectively. The residues were mixed with glycerine and mounted on glass slides for analysis using a Leitz light microscope (400× magnification). Pollen was identified following Willard et al. (2004). Identification of dinoflagellate cysts (dinocysts) was based on Rochon et al. (1999), Marret and Zonneveld (2003), Fensome and Williams (2004) and Cremer et al. (2007). The abundance of pollen and dinocysts is calculated relatively to the total sum of pollen and dinocysts, respectively. Identified plant and tree taxa are grouped into 'marsh' and 'upland' vegetation according to their highest abundance in these vegetation types (Myers and Ewel, 1990; Willard et al., 2001, Willard et al., 2006).

2.5. Diatoms

Diatom samples were treated with HCl and hydrogen peroxide (H$_2$O$_2$) to dissolve carbonate and organic matter. Diatom slides were prepared using sedimentation trays (Battarbee, 1973), Naphrax™ was used to mount the cover slips on slides. Identification is based on floras published by Cremer et al. (2007), Hustedt (1930–1966, 1955) and Witkowski et al. (2000). In general, up to 200 diatom valves were counted on each slide. Groups of polyhalobous and mesohalobous diatoms were made, based on the salinity tolerance of each species (Simonsen, 1962; Laws, 1988).

3. Results

3.1. Biomarkers

Based on biomarker assemblages, the core can be divided into a lower section (below ∼400 cmbsf) of which an example of a TLF GC trace is presented in Fig. 2A, and an upper section (above ∼400 cmbsf) for which an example of a TLF GC trace is presented in Fig. 2B. Concentration profiles (in μg/g TOC) of most abundant biomarkers and biomarkers which can be related to specific environmental conditions are presented in Fig. 3.

The steroid β-sitosterol is most abundant in the lower section and concentrations vary between 8 and 14 μg/g TOC. Taraxerol is also present in this lower section albeit in low amounts (up to 2 μg/g TOC). Between 432.5 and 352 cmbsf there is a strong increase in concentrations of taraxerol, friedelanone, dinosterol and C$_{30}$ 1,15-diol, all reaching maximum values at 352 cmbsf. Above this depth level, concentrations of these biomarkers generally decrease. In the sample at 329 cmbsf concentrations are extremely low (between 3.5 and 5 μg/g TOC). The C$_{36}$ alkenone has a similar concentration profile; however, it disappears from the record from 93 cmbsf upward. Long-chain C$_{37}$ and C$_{38}$ alkenones were absent in the lower part of the core and first recognized at a depth of ∼329 cmbsf. Subsequently, concentrations first increase up to 169 cmbsf and then decrease again. Tetrahymanol was only present in samples 389 and 352 cmbsf. Calculation of U$_{37}^{K'}$ resulted in values between 0.9 and 0.93, corresponding to temperatures between 25 and 26.2 °C. The Diol Index is 28 at 389 cmbsf and 25 at 352 cmbsf, increases up to 48 at 231 cmbsf and in the upper part increases to >70, with a maximum of 97 at 93 cmbsf. At sample depth 329 cmbsf, concentrations of C$_{30}$ and C$_{32}$ 1,15-diol were too low to be quantified, and the Diol Index could not be calculated for this depth.
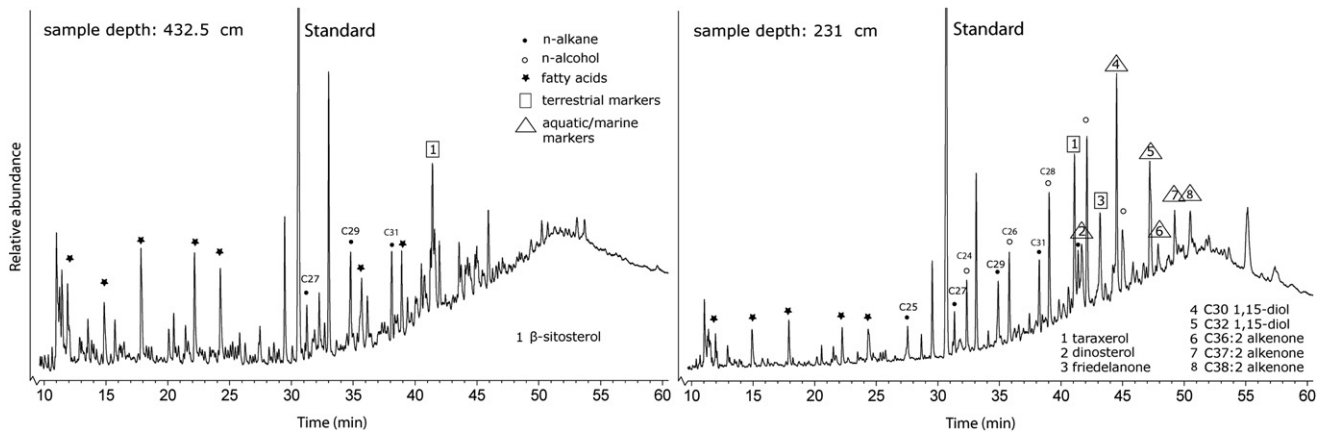
Fig. 2. Partial gas chromatograms (10–60 min) of total lipid fractions of samples 432.5 cmbsf (left) and 231 cmbsf (right).

3.2. Pollen

In general, the samples were rich in pollen and a large diversity of plant and tree taxa could be distinguished. Based on the overall changes the record can be subdivided into two distinct zones: TB-I and TB-II (Fig. 4).

Pollen zone TB-I. Amaranthaceae – *Quercus* zone (475–340 cmbsf). This zone is characterized by a variety of herbaceous taxa, of which Amaranthaceae is dominant with values up to 80% at 432.5 cmbsf, after which it decreases to 23%. Simultaneous with maximum Amaranthaceae values *Hydrocotyle* and Cyperaceae are most abundant, with maximum values of 14% for both. Following this, Poaceae (maximum of 7%), *Ambrosia* and Asteraceae Tubuliflorae and – *Iva*-type (maximum of 4%) are most abundant. This assemblage is typical for marshland. Of the trees *Quercus* is dominant, comprising up to 42% in the top of this zone. Other woody taxa found are *Carya* and *Myrica cerifera* (∼3%), and *Ulmus*, *Fraxinus*, *Ostrya* and *Nyssa* (<1%), which are common in upland forests. With values up to 14% *Pinus* is the second most abundant tree in this zone. *Taxodium* pollen does not exceed 3% of the assemblage. Mangrove taxa *Rhizophora* and *Avicennia* are present from 432.5 cmbsf up, albeit with values below 1%.

Pollen zone TB-II. Pinus zone (340–39 cmbsf). A distinct shift to mainly *Pinus* at ∼340 cmbsf marks the transition to the next zone, *Pinus* pollen comprising up to 83% of the total assemblage. *Quercus* shows a strong decrease as compared to the previous zone, but remains co-dominant (7–25%). Other tree and shrub taxa that are found do not exceed 3%. *Liquidambar* occurs for the first time in this zone, albeit with values around 1%. The different herbaceous pollen types are practically absent in this zone (<2%), with the exception of Amaranthaceae comprising up to 7%.

The bulk of the herbaceous taxa are generally found in marsh environments, whereas the identified woody taxa (with exception of mangrove species and *Taxodium*) are most common in drier upland sites (Myers and Ewel, 1990; Willard et al., 2006). Shifts in the general abundance of the two groups are given in a summarizing diagram (Fig. 4), in which *Pinus* is given separately due to its expected remote origin.

The total pollen concentration appears to be fairly constant throughout the core (∼4–10 × 10⁴ grains g⁻¹ dry sediment), with exception of two samples. At depth 432.5 cmbsf concentrations are more than doubled, mainly caused by the high abundance of Amaranthaceae pollen in this sample. A very low concentration (∼1 × 10⁴ grains g⁻¹ dry sediment) is found at 329 cmbsf.
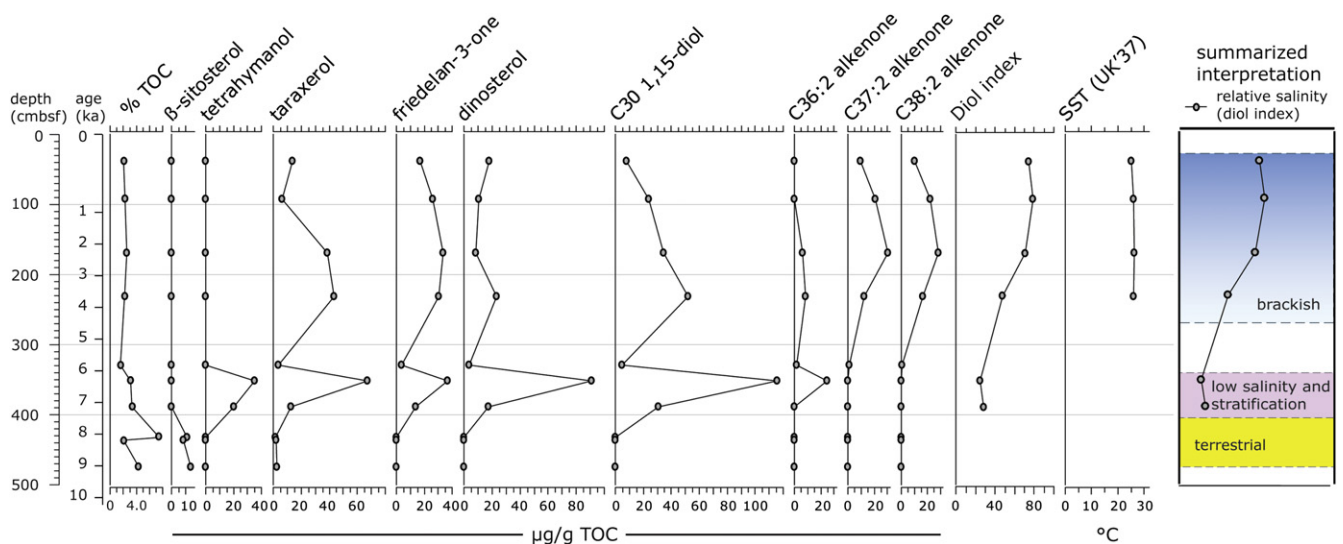

Fig. 3. Biomarker concentration profiles. Concentration of biomarkers are presented in μg/g TOC. Percentage TOC is presented at the left, at the right reconstructed SST in °C based on paleothermometer $U_{37}^{K'}$ and the Diol Index. Summarized interpretations are presented in the column at the far right.
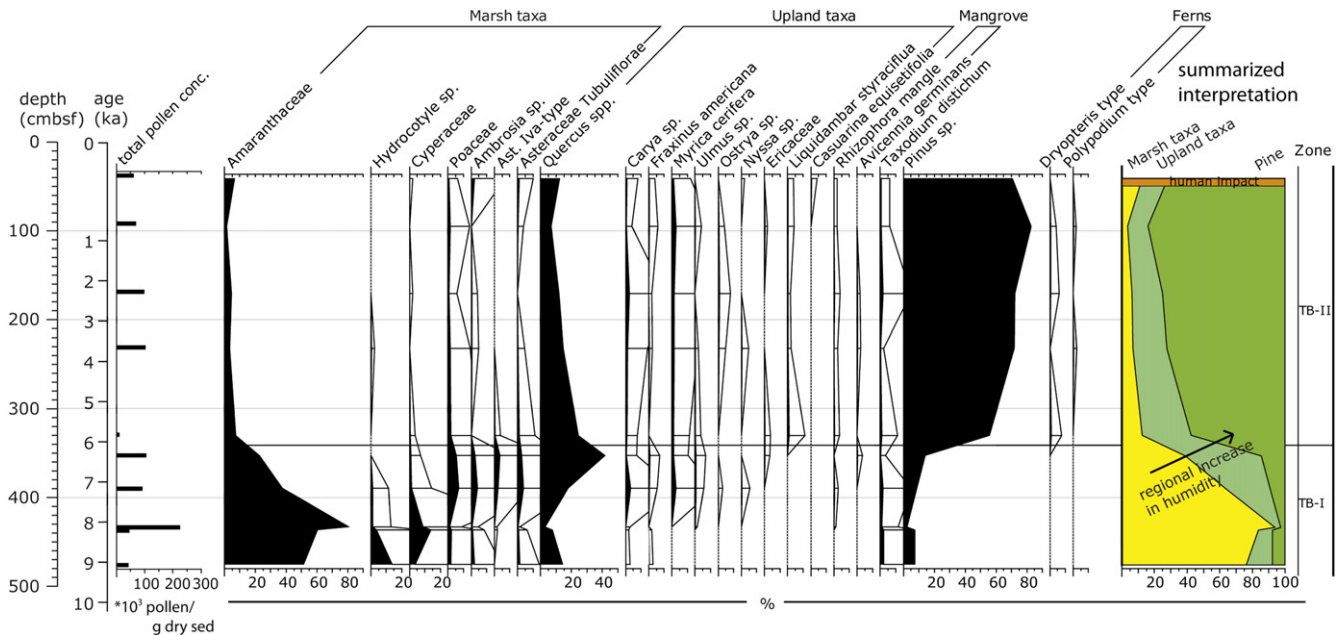
Fig. 4. Pollen percentage diagram. Percentages are calculated relative to the total pollen sum. The white areas in the diagram express a 10% exaggeration of the values for taxa with a low abundance. Total pollen concentrations in pollen per gram sediment. At the far right a composite diagram presents shifts in main vegetation communities and summarized interpretations.

3.3. Dinoflagellate cysts

Relative abundances of the most represented dinocysts are shown in Fig. 5. From the bottom of the sediment core up to 389 cmbsf no dinocysts are found. At 389 cmbsf cysts are rare, and their number is too low (11 cysts) to be considered for the reconstructions. Between 352 cmbsf and the core-top dinocysts are very abundant and their concentrations vary between ∼4 and ∼25 × 10⁴ grains g⁻¹ dry sediment. The highest concentrations are found in the lower section, between 352 and 169 cmbsf, with exception of a minimum found at 329 cmbsf (∼4 × 10⁴ grains g⁻¹ dry sediment). *Polysphaeridium zoharyi, Lingulodinium machaerophorum* and *Spiniferites* spp. are the most represented species in the assemblages. *P. zoharyi* represents about 90% of the assemblages between 352 and 231 cmbsf. Above, the relative abundance drops and the minimum value is reached at 93 cmbsf. The upper part of the core shows again a slight increase. With the decrease of *P. zoharyi* between 231 and 169 cmbsf, relative abundances of *L. machaerophorum* and *Spiniferites* spp. increase. *L. machaerophorum* reaches its maximum of 37% at 169 cmbsf, and then slightly decreases in the upper part of the core. *Spiniferites* spp. increases up to values of about 40% in the upper part of the core. Other taxa found are rare and not persistently present in the core. Only *Operculodinium* spp. has been found throughout the core and shows a peak relative abundance of about 9% at 93 cmbsf.

3.4. Diatoms

Diatom preservation is generally moderate, and occasionally poor as valves are strongly corroded and sometimes only fragments are present. Diatoms are abundant from sample depth 389 cmbsf up, with exception of sample depth 329 cmbsf which was barren. Diatoms with highest abundances are presented in Fig. 6.

The diatom assemblage at 389 cmbsf consists of more than 80% of an *Amphora* species for which further identification was not possible (Fig. 7). It resembles the marine-brackish species *Amphora gacialis*, a species of which the ecology and distribution is not well

known. Following the *Amphora*-spike, the variety in diatoms becomes wider. Between 352 and 169 cmbsf, dominant species are *Diploneis didyma, Hyalodiscus radiatus* and *Hyalodiscus scoticus, Planothidium delicatulum, Petroneis marina, Opephora* spp. and *Desikaneis gessneri*. Between samples 169 and 39 cmbsf, Plagiogrammaceae, *Amphicocconeis deculoides, Cyclotella litroalis, Actinophtychus senarius, Actinoptychus splendens* and *Paralia sulcata* are dominant. Between 7 and ∼2 ka, polyhalobous diatoms comprise about 50% of the total diatom assemblage. From ∼2 ka onwards, polyhalobous species increase relatively to mesohalobous species up to 80%.

4. Paleo-environmental reconstruction

4.1. Early-Holocene terrestrial environment

Vegetation in the Early-Holocene (500–400 cmbsf, ∼10–7.5 ka) was dominated by a variety of herbaceous taxa commonly found in fresh and brackish water marshes. β-Sitosterol is the dominant biomarker in this part of the core. It is a non-specific phytosterol generally found in vascular plants (Scheuer, 1973; Nes, 1974; Killops and Killops, 2005), and since its concentration profile is comparable to abundance profiles of *Hydrocotyle,* Cyperaceae and Amaranthaceae, here it seems mainly derived from shrubs. The pinkish white to pale brown mud in this basal part of the record, dominated by nonmarine ostracodes and molluscs, was interpreted by Cronin et al. (2007) as lacustrine.

Considering these deposits and the found pollen assemblage the site can more specifically be indicated as a wet prairie or marl-marsh (Willard et al., 2001, 2006). The absence of diatoms in this section can possibly be the result of bad preservation of these fossils in this type of environment.

The transition in marsh taxa between 9.5 and 6.5 ka, from *Hydrocotyle*/Amaranthaceae/Cyperaceae dominance to Poaceae/Asteraceae Tubuliflorae and *Iva*-type, which is a common shrub in coastal saline wetlands, is indicative for increasing salinities at the site. This trend is confirmed by the first occurrence of mangrove vegetation (*Rhizophora mangle*) around 7.5 ka, which suggests
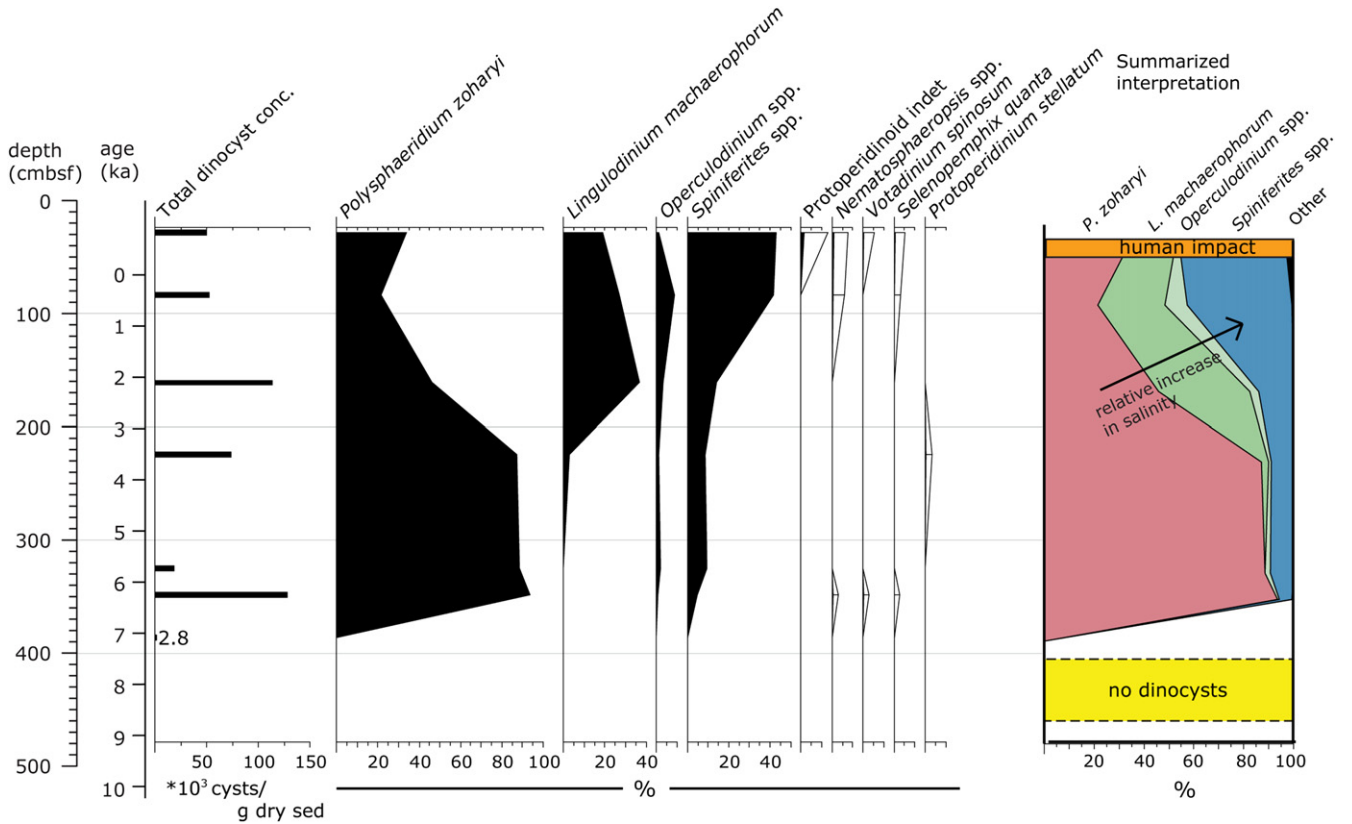
Fig. 5. Dinocysts percentage diagram. Percentages are to the total dinocyst sum. The white areas in the diagram express a 10% exaggeration of the values for groups with a low abundance. Total dinoflagellate concentrations are presented in dinocysts per gram sediment. The summary column on the right hand side of the Figure shows the major changes as inferred from the dinocysts.

a change from an inland to a more coastal setting and further increasing salinities. *Rhizophora* pollen are small and they may be partly lost during sieving (Marret et al., 2001), this does not, however, necessarily affect the trend in the pollen curve (Versteegh et al., 2004). Absence of mangrove pollen before ∼7.5 ka might indicate that the low levels of taraxerol that were detected in this
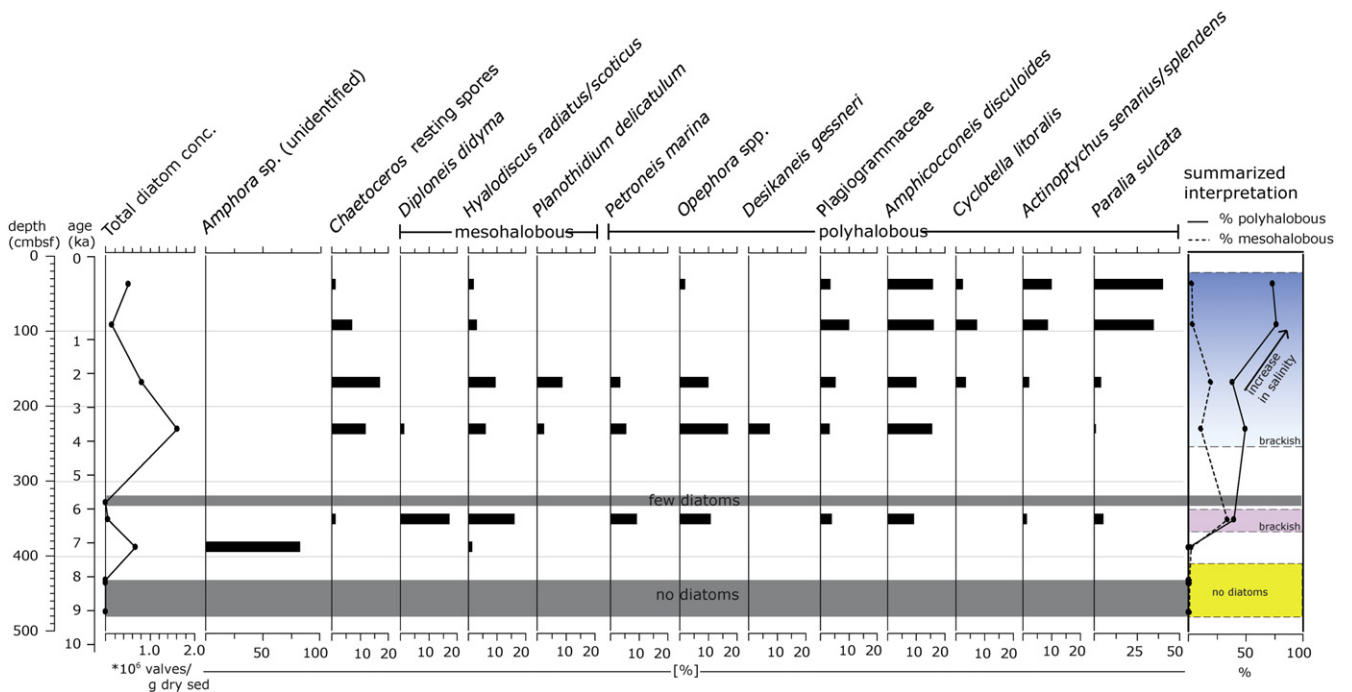

Fig. 6. Diatom percentage diagram. Percentages are calculated relative to the total diatom sum. Total diatom concentrations are presented in valves *10[6] per gram sediment. The summary column on the right presents the ratio between polyhalobous and mesohalobous species and the interpretation.
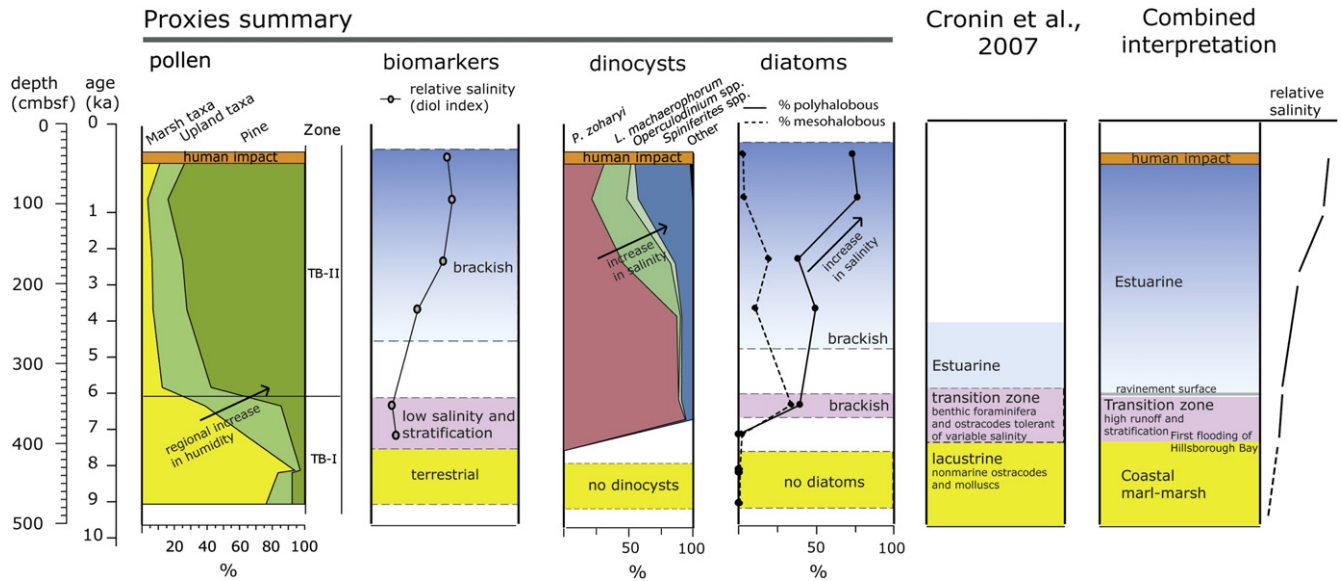
Fig. 7. Summary Figure. The graphs show the summarized interpretation for each proxy. A summarized interpretation of the study by Cronin et al. (2007) is also presented. On the far right is the combined interpretation based on the multiple proxies and results by Cronin et al. (2007).

part of the core originate from vascular plants other than mangroves (Versteegh et al., 2004 and refs therein).

The variety of upland tree pollen found in this period originate from long-distance aeolian transport, as this site was probably part of an extensive marsh with little or no upland vegetation in the area. The dominance of *Quercus* between 9.5 and 6.5 ka is in agreement with findings from inland lake records (Watts, 1969; 1971; 1975; 1980; Watts and Hansen, 1994) and was interpreted as indicative of relative aridity in Florida (Watts and Hansen, 1994).

4.2. Mid and Late Holocene marine transgression

Hillsborough Bay initially flooded around 7.5 ka. Mid and Late Holocene deposits, (400 cmbsf – top, 7.5 ka – present) contain terrestrial remains as well as aquatic remains like diatoms, dinocysts and biomarkers such as dinosterol and alkenones. The period between 7.5 and 6 ka is characterized by relative high amounts of the biomarker tetrahymanol, which derives from ciliates and is indicative for water column stratification (Sinninghe Damsté et al., 1995). Between ∼7 and 4 ka, up to 95% of the dinocyst assemblage is composed of *P. zoharyi*. This species is euryhaline, and can be found in warm and extremely stratified sea surface water environments (Marret and Zonneveld, 2003; Reichart et al., 2004; Sangiorgi et al., 2006). It can be particularly abundant in restricted marine environments like lagoons and bays and has been found abundantly in the estuarine surface sediments of Rookery Bay (Florida) (Cremer et al., 2007). Also C_{30} and C_{32} 1,15-diols are present in the sediments younger than 7.5 ka. These biomarkers most likely originate from eustigmatophytes, a group of eukaryotic algae (Volkman et al., 1992; Versteegh et al., 1997). The ratio between the two compounds, expressed in a Diol Index, is a function of salinity (Versteegh et al., 1997). Between 7.5 and 6 ka values for this index are about 25, typical for freshwater or restricted marine environments (Versteegh et al., 1997). Furthermore, long-chain C_{36} alkenones (position of double bonds at ω15,20) have their highest concentrations around 6.5 ka. These alkenones, which so far have an unknown origin, were earlier reported in sediments from the Black Sea (Xu et al., 2001) and Japan Sea (Fujine et al., 2006), where they were associated with low salinity surface water conditions. These results fit well with the idea that Tampa Bay

consisted at that time of a series of restricted lagoons, related to karst depressions (Brooks et al., 2003; Locker et al., 2003), with limited water circulation.

Around 6 ka there is a strong decrease in biomarker, pollen, dinocyst and diatom concentrations. The sample was taken from a distinct layer (sample depth 329 cmbsf), characterized by high levels of shell fragments and sand, in contrast to the mostly clayey sediments above and below this level (Cronin et al., 2007). The high amounts of shell fragments indicate a high-energy depositional environment and thus probably poor preservation or dilution of the micro-remains. Sediment cores from the shelf of west-central Florida show, in the same time period, a similar sedimentary pattern of low energy deposits, interrupted by a sharp erosional contact and followed by a coarse, but fining upward, shell layer. Brooks et al. (2003) interpreted the erosional contact as a ravinement surface and the shell layer as the initial shoreface deposition. Besides transgression, also storms will have affected sedimentation either by erosion due to storm surges or by increased runoff and consequent soil erosion. In Waccasassa Bay, north of Tampa Bay, storm driven surges were found to be an important mechanism for marsh surface accretion during the Holocene (Goodbred et al., 1998).

Increasing concentrations of friedelanone and disappearance of β-sitosterol around 7.5 ka suggest a change in vegetation cover and coincides with the terrestrial–marine transition already suggested by Cronin et al. (2007). Friedelanone, like β-sitosterol, originates from vascular plants (Scheuer, 1973; Nes, 1974; Killops and Killops, 2005). Possibly, β-sitosterol represents local herbaceous vegetation, which disappears when the environment becomes brackish. Marsh vegetation disappears almost completely from the pollen record simultaneous with the expansion of *Pinus,* between 6 and 5.5 ka. First occurrences of pollen of a number of plant and tree species like *Liquidambar* and ferns in this interval also indicate that the site became part of a more open area with a regional long-distance pollen input, rather than indicating changes in the local vegetation composition. Also friedelanone probably represents a more combined regional signal from the hinterland. The bisaccate *Pinus* pollen grains facilitate long-distance dispersal both by fluvial and aeolian transport, which might result in an over representation of this species. High levels of *Pinus* have been recovered for this period

in sites throughout the peninsula (Watts, 1969, 1971, 1975, 1980, Watts and Hansen, 1994) and the expansion of pine forest is thought to be the result of warmer winters and increased precipitation (Watts and Hansen, 1994; Grimm et al., 2006). These changes are however not clearly reflected in any of the other proxies where it is possibly overwhelmed by the response to sea-level rise.

Long-chain C_{37}–C_{38} alkenones present from ∼4 ka and onwards, are biosynthesized exclusively by certain haptophyte algae, like *Emilinia huxleyi* and *Gephyrocapsa oceanica*. Reconstructed SST, based on the global core-top calibration of Müller et al (1998) correspond well with current Tampa Bay spring temperatures of 24–26 °C (nodc.noaa.gov), the period during which major groups of phytoplankton bloom in Florida bays and on the Florida shelf (Gilbes et al., 1996; Dixon et al., 2009).

A transition to higher salinities towards the late Holocene is evident from a sharp increase in *L. machaerophorum* from 3 ka, followed by increases in *Spiniferites* spp. and polyhalobous diatoms. Also the Diol Index increases to about 80, which is typical for open marine conditions (Versteegh et al., 1997). *L. machaerophorum* has been recorded from brackish to fully marine environments, with salinity ranging between 16.9 and 36.7, while the genus *Spiniferites* is usually found in waters with salinity higher than 22 (Marret and Zonneveld, 2003). Polyhalobous diatoms have an affinity for salinities higher than 30, while mesohalobous diatoms thrive at salinities between 0.2 and 30. Combined proxies thus indicate progressing Holocene sea-level rise. A continuous marine submergence, with decelerating rates after 5 ka, was also proposed by Scholl et al. (1969).

The lowest occurrence of *Casuarina* between depth 93–39 cmbsf indicates a shift towards higher sedimentation rates in the upper part of the core. This could partly be the result of lower compaction in the upper part of the sedimentary layer. However, the increase in sedimentation rate seems rather abrupt. Brooks (in press) reported a 10-fold increase in sedimentation rates in Tampa Bay over the past century, probably as a result of increased human activities in the areas surrounding Tampa Bay. The anthropogenic impact seems however, to have had little effect on the different proxies. A small decrease in pine might indicate a change in land use and in the marine realm a slight increase in some heterotrophic dinocysts (Protoperidinioids, *Votadinium spinosum*, *Selenopemphix quanta*) could indicate a higher nutrient input and higher productivity (Marret and Zonneveld, 2003).

5. Conclusions

Combined biomarker, pollen, dinocyst and diatom records clearly show the environmental evolution of Tampa Bay under the influence of rising Holocene sea-level. Around 7.5 ka Tampa Bay is flooded and the pollen signal becomes representative of a larger catchment area. Between 7.5 ka and ∼5 ka, the bay is characterized by low salinity surface waters and water column stratification. In this period the area is certainly more sensitive to storm and hurricane activity and the associated storm surges likely resulted in sedimentary hiatuses and/or storm deposits. Aquatic and marine proxies indicate increasing salinities from 7.5 ka to the present, which is likely the consequence of sea-level rise following the last deglaciation. Around 6.5 ka, a change in vegetation from *Quercus* to *Pinus* indicate a regional change towards more humid conditions. Reconstructed SST for the past 4 kyrs are between 25 and 26 °C and indicate stable temperatures during this period. A sharp increase in sedimentation rate in the top ∼50 cm of the core is ascribed to human impact and coherent with other studies in the surroundings of Tampa Bay.

This environmental interpretation is in agreement with Cronin et al. (2007) who recognized a transition from lacustrine to estuarine conditions around 7.5 ka in the same sediment core. While the previous study established the presence of sea-level rise at this site, this study provides a more detailed interpretation of the environment, like the transition from fresh to brackish/marine conditions. Proxies are in agreement with each other, which makes the environmental interpretation reliable. At the applied resolution, the marine signal is determined by the rising sea-level. When higher resolution will be achieved; changes in SST, humidity and salinity can provide information on past changes in the climate system and the effects in this area.

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