



Reconstruction of climate-induced environmental changes in the eastern Gulf of Mexico based on foraminifera sediment assemblages

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ABSTRACT

Foraminifera assemblages are powerful bioindicators of environmental change and were analyzed in a sediment core collected from the Marquesas Keys, located in the southwestern region of the Florida Keys. The composition and abundance of foraminifera tests within the top 85 cm of the sediment core, dated with ¹⁴C and ²¹⁰Pb, revealed changes in foraminifera assemblages in 1990 CE, 1939 CE, and 1872 CE. Based on the ecological preferences of the dominant species, changes in salinity and submerged aquatic vegetation (SAV) cover may have influenced foraminifera species composition. These changes were likely caused by variation in precipitation patterns in the eastern Gulf of Mexico region associated with shifts in the major ocean-atmosphere teleconnections such as the El Niño Southern Oscillation (ENSO), Atlantic Multidecadal Oscillation (AMO), North Atlantic Oscillation (NAO) along with tropical storms and hurricanes. Prolonged periods of the negative phases of these climate phenomena coincided with shifts in foraminifera assemblages. Despite a generally negative impact of the ocean-atmosphere teleconnections on the South Florida region, a well-developed epiphytic assemblage was recorded in the studied core. The assemblage was recorded in the uppermost part of the core and dated to the period between 1990 and 2010 CE. This implies that a dense SAV community was present within the Marquesas Keys Mooney Harbor since at least the early 1990.

1. Introduction

Foraminifera are unicellular eukaryotic organisms characterized by high diversity and abundance which mostly inhabit marine waters but also occur in brackish waters and freshwater environments (Holzmann et al., 2003). The cytoplasmic body of foraminifera is covered by an organic or mineralized test (shell). The latter may be preserved in many types of sediments providing an extensive fossil record that dates back to the Cambrian period ~500 million years ago (Loeblich and Tappan, 1987). Foraminifera are useful indicators of past and present-day environmental conditions (Murray, 1991, 2006). They interact with other components of meio- and macrofauna and are influenced by a combination of abiotic (e.g., temperature, salinity, currents, light, dissolved oxygen, nutrients, pH, trace elements and substrate) and biotic factors (e.g., interaction with other organisms for space and food, symbiosis,

grazing, parasitism (Boltovskoy and Wright, 1976; Murray, 2006). Some species with narrow ecological niches are more sensitive to environmental changes, while others can tolerate wider variations of environmental conditions (Murray, 1991). Due to their high fossilization potential, worldwide occurrence, high abundance, high turnover rate and quick response to environmental changes, foraminifera are used to infer changes in climate, physico-chemical ocean properties and sea level over centennial and millennial time scales (Brewster-Wingard and Ishman, 1999; Horton et al., 1999; Murray, 2006; Cheng et al., 2012; Schönfeld et al., 2012).

Recent paleoecological investigations in Florida Bay and Biscayne Bay in South Florida revealed that changes in salinity and seagrass cover caused by the major hydrologic alteration of the South Florida ecosystems over the last 150 years of climate change and extreme weather events, resulted in significant shifts in foraminifera assemblages

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structure during that time (Brewster-Wingard and Ishman, 1999; Ishman, 2000). Collins et al. (2019) reconstructed the Florida Bay seagrass cover shifts using epiphytic foraminifera as a proxy. Recent seagrass die-offs in Florida Bay were attributed to a combination of anthropogenic factors and climatic and meteorologic factors (Zieman et al., 1999; Borum et al., 2005; Hall et al., 2016).

The Gulf of Mexico and Southern Florida climatic conditions are influenced by ocean-atmosphere teleconnections, specifically the tropical Pacific El Niño Southern Oscillation (ENSO), the Atlantic Multi-decadal Oscillation (AMO), and the North Atlantic Oscillation (NAO), which drive the regional and local environmental conditions in terms of salinity, currents and precipitation (e.g. Hurrell, 1995; Enfield et al., 2001; Briceño and Boyer, 2010). They impact salinity conditions through their drier negative and wetter positive phases. Wachnicka et al. (2013a, 2013b) described historical changes in salinity based on biological proxies preserved in Florida Bay and Biscayne Bay cores, and determined that those changes at partially coincided with variations of ocean-atmosphere teleconnections.

Extreme weather events (e.g., hurricanes, winter storms) also significantly affect the South Florida marine ecosystems. Hurricanes frequently, although irregularly, pass through the region and the strongest storms can result in wind speeds exceeding 280 km per hour (<https://coast.noaa.gov/hurricanes/#map>) and heavy rainfall over large areas causing regional flooding, coastal erosion and sediment transport, and massive inflows of freshwater into coastal regions. Over the last 150 years, numerous hurricanes passed through the South Florida region, with some being strongly destructive for the marine, coastal and mainland environments. Recent hurricanes impacting the region include hurricanes Andrew in 1992, Wilma in 2005 and Irma in 2017. All of them were responsible for coastal sediment erosion, water quality impairments and submerged aquatic vegetation (SAV) uprooting. Analysis of the historic hurricane tracks revealed that the Marquesas Keys were mostly spared from the most destructive hurricanes over the last 150 years (<https://coast.noaa.gov/hurricanes/#map>). The Keys were directly hit by two category 2 hurricanes, the unnamed 1876

hurricane with wind speeds up to 145 km/h and Hurricane Inez in 1966 with wind speeds up to 138 km/h.

Here we describe, for the first time, changes in foraminifera assemblages and geochemical proxy-records preserved in a sediment core collected from a central lagoon within the Marquesas Keys, dating back to 228 BCE. Our main goal was to: 1) reconstruct past environmental changes in the Marquesas Keys area and 2) identify the possible drivers of those changes.

2. Study area

The Marquesas Keys comprise 14 uninhabited mangrove islands that encircle a shallow basin known as Mooney Harbor positioned ca. 25 miles west of Key West and 45 miles east of Dry Tortugas (Fig. 1). This region is part of the Florida Keys National Marine Sanctuary and includes the third largest coral reef system in the world. Inside Mooney Harbor are <2 m deep seagrass beds consisting mainly of *Thalassia testudinum* interspersed with sponges, macrophytes and hard bottom (Shinn et al., 1990; Bresette et al., 2010). The shallow seagrass beds are cut by sinusoidal tidal channels 2–3 m deep, which allow flow into and out of Mooney Harbor. The lagoon also includes sandy calcareous depressions, that are 1–3 m deep, 20–350 m long, and 20–60 m wide, within the shallow seagrass beds. At the lowest tides, shallow seagrass flats become exposed, isolating the depressions (Bresette et al., 2010). The vegetated ring of islands forms a wave-and-current barrier that protects the central lagoon from erosion, producing a low-energy area that traps fine-grained sediments (Lidz et al., 2007).

3. Materials and methods

3.1. Core collection

A set of duplicate sediment cores were collected from the northern region of the Marquesas Keys lagoon in February 2013 (Fig. 1). The cores were collected using a piston coring device equipped with a

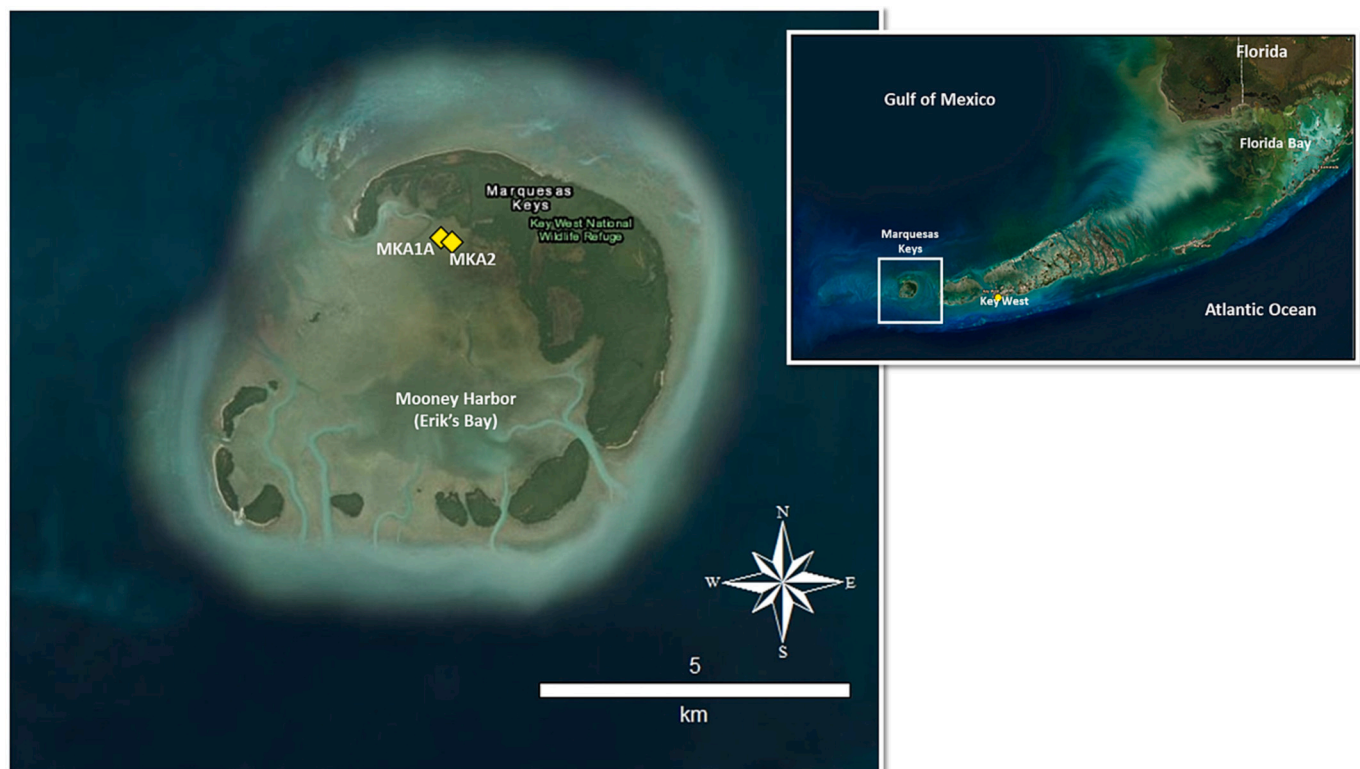


Fig. 1. Study area. MKA1A and MKA2 mark the coring site location.

mounted tripod winch and an 11.4 cm diameter polycarbonate tube, with a piston positioned at the sediment surface at the start of coring. The sediment core tubes were pushed into the sediment and then retrieved using the tripod winch. The top and bottom of the tubes were capped to prevent sediment loss. The cores were imaged by X-ray and computerized tomography (CT) scans to determine the presence of bedding and lamination and the extent of sediment disturbance (e.g., bioturbation). One core was sectioned into 1-cm slices for geochemical analyses and samples for foraminifera analyses were collected at 4 cm intervals. The second core was stored at the University of Miami (Miami, Florida) core repository as an archive. In total, 86 samples were analyzed for geochemistry and 22 samples were analyzed for foraminifera from a total core length of 85 cm.

3.1.1. Sediment dating

Age models for the cores were developed by using lead 210 (^{210}Pb ; for sediments younger than 150 yr) and carbon 14 (^{14}C ; for sediments older than 150 yr) radiometric methods. The ^{210}Pb method was used to determine the age of the last century deposits (0–23 cm), while shell fragments found in the deeper sediments were dated by using ^{14}C method to determine the age of older deposits (36–77 cm). The ^{210}Pb dating was performed in the radiometric dating laboratory at the St. Croix Watershed Research Station in the Minnesota Museum of Natural History (Minnesota, U.S.A.), while the ^{14}C dating was performed at the Poznań Radiocarbon Laboratory (Poznan, Poland) using accelerator mass spectrometry.

Precise ^{210}Pb sediment ages were produced over the depth range of

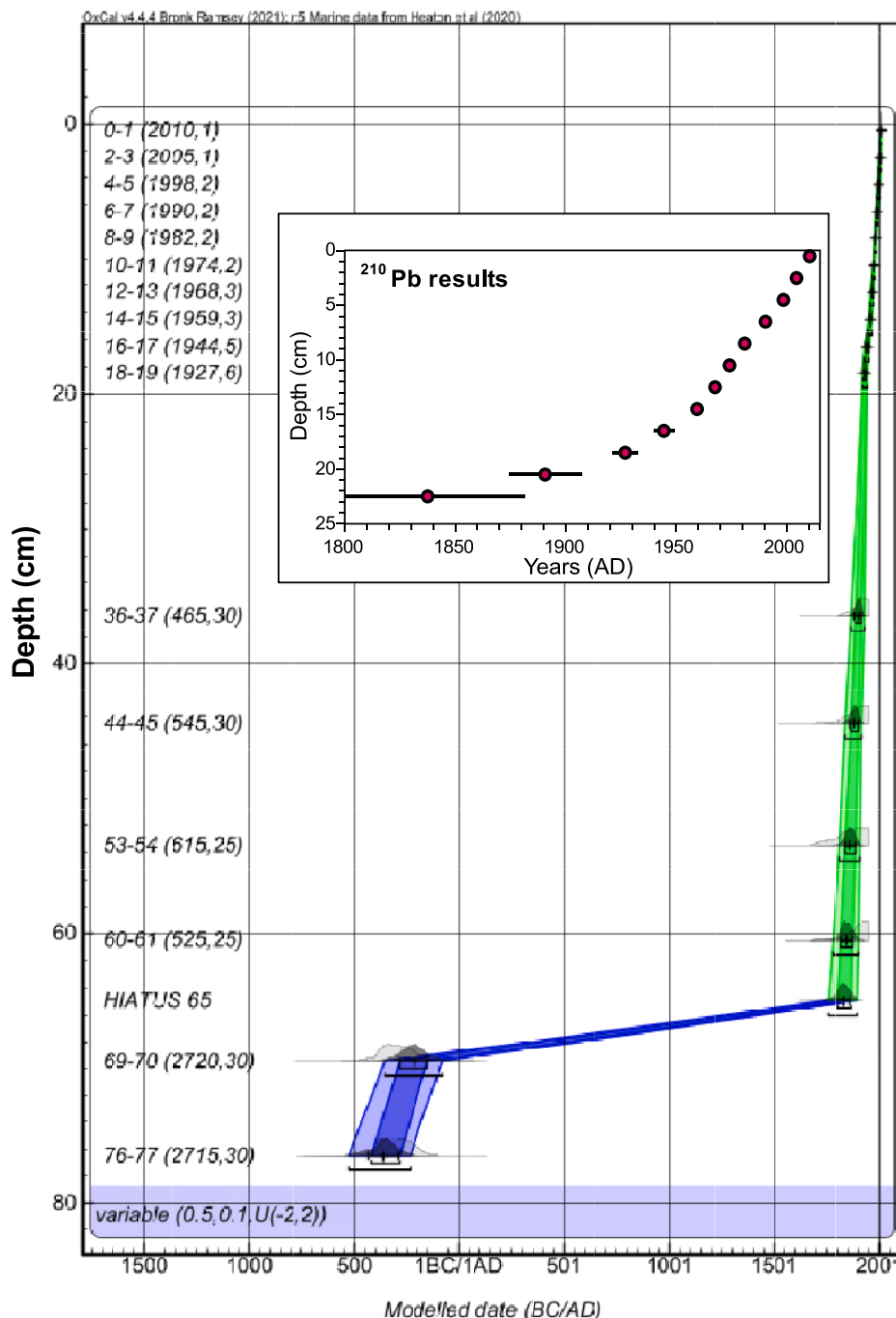


Fig. 2. The integrated age depth model of the sediment core from Marquesas Key based on combined ^{14}C and ^{210}Pb datings. Note the presence of the hiatus at ~65 cm b.s.f. The ^{210}Pb dates plotted versus the sediment depth in the inset.

0–19 cm, with ± 16 error of up to 5.5 years. Error for the age estimates at 20 and 22 cm were higher and amounted to 16 and 44 years, respectively. These two samples with the highest error were excluded, leaving ten uppermost samples in the time span between 2010 and 1939 CE included in the age model. Six radiocarbon dates were also obtained, representing time period between 465 and 2715 yr BP (Fig. 2). These dates were included in the age – depth model using OxCal v4.4.4 (Bronk Ramsey and Lee, 2013; Bronk Ramsey, 2017, 2021; Heaton et al., 2020). The calibration of radiocarbon dates was performed with marine calibration curve Marine20 (Heaton et al., 2020). The model was created with command PSequence and the parameter k value at 0.5. None of the dates showed an inversion. Fit of the model amounted to 69.5%, indicating good fit and accurate model assumptions.

3.1.2. Geochemical analyses

Sediments were analyzed for total nitrogen (TN), total phosphorus (TP), dissolved inorganic carbon (DIC) and total organic carbon (TOC) at the Nutrient Analysis Core Facility at the Institute of Environment, Florida International University, Miami (Miami, FL; <https://environment.fiu.edu/facilities-research-groups/cache-nutrient-analysis-core/>). TN, DIC, and TOC were determined using a Carlo Erba CHN NA1500 Series analyzer following the procedures described by USGS (2007). Samples for TOC analysis were acidified with 3 N HCl and then purged for 6 min with CO₂-free air in order to remove DIC immediately prior to analysis. Non-acidified samples were used to measure total carbon (TC). DIC was calculated by subtraction of TOC from TC. TP was determined following the methodology of Fourqurean et al. (1992) which is a modification of the method described by Solórzano and Sharp (1980).

Elemental analyses were performed with Avatech X-Ray Fluorescence Core Scanner and a GEOTEK Multi-Sensor Core Logger enabling rapid and non-destructive measurements of geochemical and geophysical properties of the sediment core at the Core Imaging Laboratory, University of Miami (Florida, USA, <https://marine-geosciences.earth.miami.edu/research-themes/paleoclimatology-and-geochemistry/core-imaging-laboratory/index.html>).

3.1.3. Micropaleontology

Approximately 10 g of wet sediment samples were collected at 4 cm intervals throughout the core and were washed over a 125 μ m sieve (Schönfeld et al., 2012). A total of 6792 foraminifera (all samples) and a minimum of 153 and a maximum of 719 individual specimens were picked from the residue of each sample. All specimens were arranged by taxon on micropaleontological slides and counted. Photographic documentation of specimens typical of the key species used for defining foraminifera assemblages was performed with a Leica Z16 APO stereoscopic microscope at the Department of Paleontology, University of Vienna (Vienna, Austria). Photomicrographs of foraminifera species were stacked using the CombineZP software (Brecko et al., 2014). Electron micrograph images were produced using a JEOL JSM-6400 scanning electron microscope at the Department of Paleontology, University of Vienna. The classification scheme used here is that of Buzas et al. (1977), Buzas and Severin (1982), Loeblich and Tappan (1987) and the WoRMS database (World Register of Marine Species; Hayward et al., 2021).

3.2. Data sources and analysis

Historical data on regime shifts in ENSO, AMO, NOA indices were obtained from <https://www.ncei.noaa.gov/> and PDSI indices were obtained from <https://www.ncei.noaa.gov/>. The El Niño 3.4 ENSO index for 1870–2010 (anomaly from 1981 to 2010), AMO for 1856–2010 (unsmoothed from the Kaplan SST V2) and NAO for 1845–2010 (normalized pressure difference between Gibraltar and SW Iceland) were obtained from https://psl.noaa.gov/gcos_wgsp/Timeseries/. The Florida Palmer Drought Severity Index (PDSI) data for years 1895–2010 expressed as anomaly from the base period 1901–2000 were obtained

from <https://www.ncei.noaa.gov/>.

To improve our understanding of the foraminifera record, their abundances were statistically analyzed using Q-mode principal component (PC) analysis with a significant PC loading threshold of 0.4 (Malmgren and Haq, 1982), using a commercially distributed statistics package (SYSTAT 12). The orthogonal Varimax rotation was used to improve the detection of clusters of sample units and align ordination axes along gradients of maximum variance. This serves to increase the contrast between species assemblages by increasing high correlations and decreasing low correlations of the individual variables (McCune and Grace, 2002). This eases the interpretation of the ordination and clarifies the relationship among factors (Malmgren and Haq, 1982). After removing taxa with <1% relative abundance of the entire fauna, 53 taxa were included in the analysis. Shannon diversity index (H') was calculated using PAST4.03 software (Hammer et al., 2001).

4. Results

4.1. Sediments characterization and dating

Visual inspection of the core revealed that the Marquesas Keys core was composed of light grey, fine-grained carbonate mud interspersed with layers of sandy mud and containing shell fragments and unidentified plant remains. Computerized tomography (CT scan) images were produced to detect evidence of bioturbation or disruption of sedimentary layers. The age model indicated a time span between ca. 520 BCE (depth of 76–77 cm) and 2010 CE (depth of 0–1 cm, Table 1, Fig. 2). Presence of the hiatus at the depth range of 61–69 cm, encompassing ca. 2000 years was detected as well (Table 1, Fig. 3).

Sediment accumulation rates were calculated based on the age – depth model estimates (Fig. 2). Sediments to a depth of 61 cm (ca. 1847 CE) have shown a decreasing accumulation rate tendency from 3 to 5 mm/year at the uppermost 0–20 cm (2010–1939 CE) surface sediments to ca. 1 mm/year at 20–61 cm (1939–1847 CE). The lowest estimated deposition rate of 0.14 mm/year was observed for the lowermost interval of 70–75 cm (older than 228 BCE) part of the core studied (Fig. 4).

4.2. Geochemistry

The biogeochemical proxies (IC, TOC, TN and TP) show very similar patterns in the sediment interval of 20–85 cm (1939 CE–434 BCE) followed by a strong and rather abrupt changes in the sediment uppermost interval of 0–20 cm (2010–1939 CE; Fig. 4, Supplementary 1). The content of the IC in the lower part of the core oscillates around ca. 10% and shows no distinct changes. Fairly similar is the TOC content, which oscillates in this part of the core around 2%. At the sediment depth of 18 cm (1939 CE), these two parameters show significant changes and their net effects are opposite to each other. While IC is decreasing from 10 to 8% at the depth of 10 cm (ca. 1980 CE) and then increasing again to 9% at the core top (2010 CE), TOC shows an increase from 2 to ca. 8% at 8 cm (1988 CE) with a minor decrease to 6% between 15 and 12 cm (1959–1968 CE) followed by quite strong increase up to 8 cm (ca. 1990

Table 1
Modeled ages of the key periods in the Marquesas Keys core record.

Depth (cm below sea floor)	Modeled age (AD)
0	2010
6.5	1990
18.5	1939
36.5	1900
48.5	1872
55	1858
60	1847
70	–228
80	–434 *

* extrapolated.

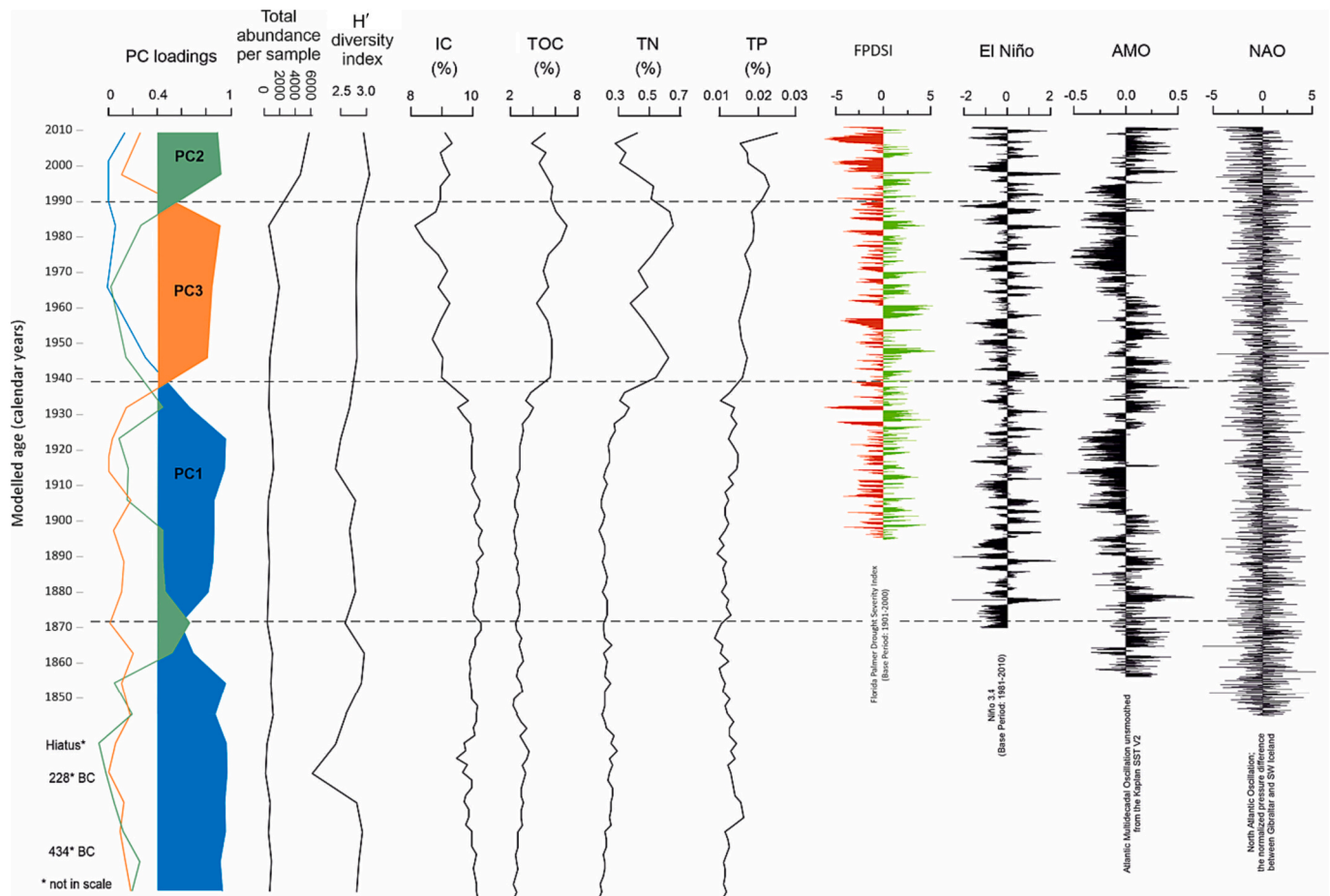


Fig. 3. Stratigraphic summary of PC loadings for the foraminifera assemblages, total foraminifera abundance, H' diversity index, geochemical proxies (IC – inorganic carbon, TOC – total organic carbon, TN – total nitrogen, TP – total phosphorus), and reconstructed climatic indices (FPDSI = Florida Palmer Drought Severity Index, El Niño Southern Oscillation, Atlantic AMO = Multidecadal Oscillation, and NAO = North Atlantic Oscillation). Statistically significant PC loading values (> 0.4 , Malmgren and Haq, 1982) are indicated with blue (PC1), green (PC2), and orange (PC3) color fills. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

CE) and finally with a decrease to 4% at the surface (2010 CE). The distribution of TN in the core resembles that of TOC, with a slightly increasing trend from 0.3 to 0.5% at the sediment interval of 18–85 cm (1939 CE–434 BCE). Significant changes in TN are first observed at 18–16 cm (ca. 1939–1944 CE) increasing to 0.6% with a minor decrease to 0.4% between 15 and 12 cm (ca. 1960–1970 CE). From the depth of 12 cm (1970 CE) TN shows a decrease to ca. 0.3% at the sediment surface. TP varied little throughout the core with concentrations around 0.01% over the entire core depth with only slight increase to 0.02% within the topmost 18 cm of the sediment (1939–2010 CE).

4.3. Micropaleontology

A total of 77 benthic foraminifera taxa (Fig. 4, Supplementary 2) was identified in the Marquesas core. The extrapolated estimated density of foraminifera tests was 1380/g dw sediment in the surface layer (2010 CE), decreasing to 170/g dw sediment at 8–9 cm (1990 CE) below sea floor (b.s.f.), and never exceeding 450/g dw sediment per sample further down the core (Fig. 3).

Analyses of the foraminifera species abundance, distribution, and diversity within the studied sediments show distinct changes in the core profile (Fig. 3). In the lowermost part of the core, significant decreases in abundance and species diversity were observed. The lowest values were associated with a hiatus spanning between ca. 228 BCE and 1847 CE, with the H' diversity index of 1.95 (228 BCE) and lowest abundance of 181 specimens in the same sample. From ca. 1850 CE, H' diversity index

increases and oscillates between 2.5 and 3.0, with a decrease below 2.5 dated to ca. 1910–1920 CE (Fig. 3). The species composition in this part of the core changes from a dominance of *Cibicides lobatulus* (oscillating between 23 and 48%) in the sediment layers older than ~1850 CE to a dominance of *Quinqueloculina candeiana* (15%) from 1850 to 1939 CE. During the short period between 1860's and early 1870's these taxa were replaced by the epiphytic forms *Hauerina earlandi* (formerly *Heterillina cribrostoma*), *Quinqueloculina laevigata* and *Rosalina floridana*. In the sediment interval dated to 1939–1920 CE, a strong decrease in *C. lobatulus* and *Q. candeiana* was observed. These taxa were replaced by a significant increase in *Quinqueloculina boschiana*, *Q. poeyana* and *Pseudotriloculina linneiana* and an unidentified juvenile specimens of *Quinqueloculina* spp., which were dominant in the sediment dated to ca. 1939–1990 CE. In the uppermost sediment layer dated to 1990–2010 CE, the latter taxa strongly decrease and were replaced by *H. earlandi* (up to 10%), *Miliolinella circularis*, *Quinqueloculina laevigata* and *R. floridana* (up to 16%). In this part of the core, a significant increase in foraminifera abundance from ~1000 (ca. 1985 CE) to ~6000 (2010 CE) specimens was observed (Fig. 3).

4.4. Foraminifera assemblages

The Q-mode PC analysis revealed three principal components (PCs) that explained 87.2% of the total variance in the dataset. PC1, PC2, and PC3 accounted for 59.8%, 15.9%, and 11.4% of the total variance, respectively. Foraminiferal assemblages (FAs) were identified and

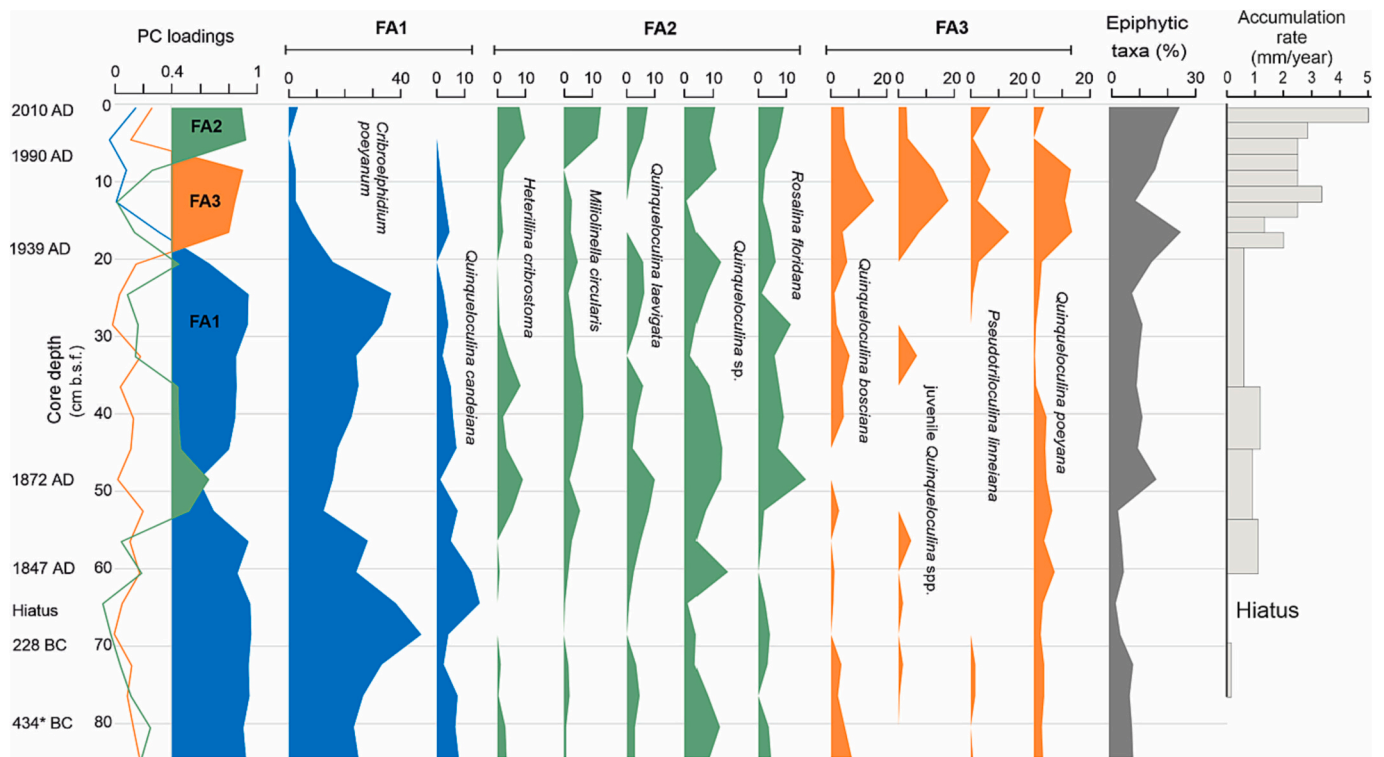


Fig. 4. Stratigraphic summary of sediment depths, modeled ages, foraminifera species relative abundances (%), epiphytic taxa (%), and sediment accumulation rate (mm/year). Statistically significant PC loading values (> 0.4 , Malmgren and Haq, 1982) and the corresponding dominant foraminifera of the foraminifera assemblages (FA) are indicated with blue (FA1 = *Criboelphidium poeyanum* FA), green (FA2 = *Quinqueloculina* sp. – *Miliolinella circularis* FA), and orange (FA3 = *Quinqueloculina poeyana* – juvenile *Quinqueloculina* FA) color fills. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

defined by two to five taxa having the highest positive principal component (PC) scores on each of the principal components. These taxa are marked in bold in Table 2. The three separate FAs were referred to using the name of the dominant taxon or pair of taxa with similarly high PC scores, underlined in Table 2. FA1 was defined by *Criboelphidium poeyanum* and *Quinqueloculina candeiiana*. FA2 was defined by juvenile *Quinqueloculina* spp., *Miliolinella circularis*, *Rosalina floridana*, *Hauerina earlandi*, and *Quinqueloculina laevigata*. FA3 was defined by *Quinqueloculina poeyana*, juvenile *Quinqueloculina*, *Quinqueloculina bosciiana* and *Pseudotriloculina linneiiana*. The dominant foraminifera taxa are illustrated in Fig. 5.

The prevalence of these FAs in the sedimentary record is indicated by PC loadings of their associated PC > 0.4 (Figs. 3 and 4). The sedimentary record was dominated by the *Criboelphidium poeyanum* FA (FA1), particularly before 1939. The unidentified juvenile *Quinqueloculina* spp., *Miliolinella circularis* FA (FA2) dominated during the period between 1939 and 1990. The *Quinqueloculina poeyana* – juvenile *Quinqueloculina* FA (FA3) dominated in the most recent period dating back to 1990.

5. Discussion

5.1. Interpretation of the intervals dominated by different FAs

The three foraminifera assemblages established for the Marquesas Keys core are similar to those in neighboring Florida Bay and reflect the major environmental changes taking place in the region.

5.1.1. FA1

The first foraminifera assemblage (FA1) was dominant from the bottom of the record at 85 cm b.s.f. (ca. 434 BCE) up to 1939 CE with a ca. 2000-year hiatus between ca. 200 BCE and 1847 CE. The period of dominance of FA1 assemblage is characterized by the lowest abundance

and in some intervals relatively low diversity of foraminifera as compared to the later periods. The accumulation rate is low to very low, ranging from ca. 1.0 to 0.5 mm/year. Sediments dominated by FA1 show rather low and monotonous contents of IC, TOC, TN and TP. While IC shows a gentle decrease from 10 to 8%, TOC, TN and TP show slight increase in this part of the cores. TOC content increases from 2 to 4%, TN from 0.3 to 0.5% and from 0.01 to 0.02%. A short decline and change from FA1 to FA2 dated to the turn of 1860's and 1870's AD was associated with distinct and prolonged negative phase of ENSO index which results in decreasing precipitation (dry conditions). A shift from FA1 to FA3 dated to 1939 CE seems correlated with an overlap in positive phases of ENSO, AMO, Palmer Drought Severity Index (PDSI) and negative NAO phase (Fig. 3).

The FA1 foraminifera assemblage, i.e., the *C. poeyanum* FA, dominates in the core prior to 1939 CE and down to ca. 500 BCE. This period included the ca. 2000 year hiatus at 61–69 cm b.s.f. spanning time period between ca. 200 BCE and the first half of the 19th century. Except for the period of early 1870's (1872 CE) when the FA1 assemblage is shortly replaced by FA2, taxa defining FA1 (Fig. 4) are dominant.

The nominative species of FA1 *C. poeyanum* is a common member of marginal marine assemblages (Brewster-Wingard and Ishman, 1999; Ishman, 2000; Cheng et al., 2012; Ellis et al., 2018; Haller et al., 2019) that are negatively correlated with phytodetritus (Brasier, 1975). The presence of other elphidid foraminifera, in the older parts of the core where FA1 dominates, indicates euryhaline salinities (Murray, 1991), suggesting periods of temporarily reduced salinity, possibly related to increased rainfall. It is difficult to unequivocally confirm this relation, as the PDSI for the period 1895–1939 shows short but strong negative phases (Fig. 3). In a foraminifera-based reconstruction of salinity trends for Central Florida Bay, Brewster-Wingard and Ishman (1999), infer brackish water conditions with salinity ranging from 18 to 25 psu for the period of 1880–1900 CE, but for 1900–1920 CE an increase in salinity

Table 2

Foraminifera PC scores. The PC scores >1 and < -1 (in bold) show significant contribution of the selected variables (foraminifera species) for each foraminifera assemblage (Malmgren and Haq, 1982). The nominative taxa of the foraminifera assemblages are underlined.

Taxon	PC1	PC2	PC3
Percent of total variance explained	59.8	15.9	11.4
<i>Affinetrina bassensis</i> (Parr, 1945)	-0.35	-0.17	-0.49
<i>Ammonia</i> sp.	-0.15	-0.55	-0.42
<i>Archaias angulatus</i> (Fichtel & Moll, 1798)	-0.19	0.53	-0.25
<i>Articulina mucronata</i> (d'Orbigny, 1839)	-0.34	-0.24	-0.12
<i>Articulina pacifica</i> Cushman, 1944	-0.06	-0.34	-0.08
<i>Pseudolachlanella eburnea</i> (d'Orbigny, 1839)	-0.40	0.40	-0.16
<i>Bolivina lanceolata</i> Parker, 1954	-0.16	-0.48	-0.43
<i>Bolivina lowmani</i> Phleger & Parker, 1951	-0.29	-0.50	-0.22
<i>Bolivina</i> sp.	-0.22	-0.49	-0.44
<i>Buliminella elegantissima</i> (d'Orbigny, 1839)	-0.24	-0.47	-0.44
<i>Bulimina</i> sp.	-0.26	-0.46	-0.44
<i>Elphidium mexicanum</i> Kornfeld, 1931	0.26	-0.17	-0.53
<i>Elphidium galvestonense</i> Kornfeld, 1931	0.30	-0.41	-0.42
<i>Criboelphidium gunteri</i> (Cole, 1931)	-0.26	-0.46	-0.44
<u>Criboelphidium poeyanum</u> (d'Orbigny, 1839)	6.79	-0.45	0.00
<i>Cyloforina sidebotomi</i> (Rasheed, 1971)	-0.22	-0.22	-0.46
juvenile <i>Elphidium</i> spp.	-0.29	-0.50	-0.22
<i>Elphidium sagra</i> (d'Orbigny, 1839)	-0.26	-0.46	-0.44
<i>Elphidium</i> sp.	0.38	-0.68	0.09
<i>Haynesina depressula</i> (Walker & Jacob, 1798)	0.45	-0.15	-0.59
<i>Hauerina earlandi</i> Rasheed, 1971	-0.43	2.71	-0.38
<i>Neonoronina orbicularis</i> (Terquem, 1876)	-0.20	-0.48	-0.46
<u>Miliolinella circularis</u> (Bornemann, 1855)	-0.41	3.31	-0.34
<i>Miliolinella californica</i> Rhumbler, 1936	-0.31	-0.31	-0.47
<i>Nodobacularella cassis</i> (d'Orbigny, 1839)	-0.30	-0.33	-0.44
<i>Nonion</i> sp.	-0.26	-0.46	-0.44
<i>Pseudononion japonicum</i> Asano, 1936	-0.24	-0.46	-0.43
<i>Quinqueloculina bicarinata</i> d'Orbigny in Terquem, 1878	0.12	0.05	-0.56
<i>Quinqueloculina bicostata</i> d'Orbigny, 1839	-0.34	-0.55	0.50
<i>Quinqueloculina bosciiana</i> d'Orbigny, 1839	-0.12	0.41	2.72
<i>Quinqueloculina bradyi</i> McCulloch, 1977	0.02	-0.41	-0.10
<i>Quinqueloculina candeiana</i> d'Orbigny, 1839	1.17	-0.51	0.42
<i>Quinqueloculina carinata</i> d'Orbigny, 1850	-0.33	-0.21	-0.27
<i>Quinqueloculina crassa</i> d'Orbigny, 1850	-0.22	-0.50	-0.43
<u>juvenile Quinqueloculina</u>	-0.51	-0.63	3.88
<i>Quinqueloculina lamarckiana</i> d'Orbigny, 1839	-0.29	-0.47	-0.33
<i>Quinqueloculina laevigata</i> d'Orbigny, 1839	0.13	2.16	-0.82
<i>Pseudotriloculina linneiana</i> (d'Orbigny, 1839)	-0.48	-0.06	2.24
<i>Pseudotriloculina rotunda</i> (d'Orbigny in Schlumberger, 1893)	-0.08	-0.33	-0.45
<i>Quinqueloculina poeyana</i> d'Orbigny, 1839	0.10	-0.28	3.91
<i>Quinqueloculina polygona</i> d'Orbigny, 1839	-0.34	0.39	0.53
<i>Quinqueloculina seminulum</i> (Linnaeus, 1758)	-0.02	0.81	0.66
<u>Quinqueloculina</u> sp.	0.84	3.41	0.77
<i>Planorbulina mediterraneensis</i> d'Orbigny, 1826	-0.28	-0.44	-0.44
<i>Pyrgo</i> sp.	-0.20	-0.47	-0.43
<i>Rosalina subaraucana</i> (Cushman, 1922)	-0.23	-0.46	-0.42
<i>Rosalina floridana</i> (Cushman, 1922)	0.16	2.89	-0.38
<i>Rosalina</i> sp.	-0.17	-0.33	-0.35
<i>Spiroloculina ornata</i> d'Orbigny, 1839	-0.28	-0.33	-0.49
<i>Textularia oviedoiana</i> (d'Orbigny, 1839)	-0.10	-0.48	-0.47
<i>Triloculina bicarinata</i> d'Orbigny, 1839	-0.24	-0.46	-0.45
<i>Triloculina trigonula</i> (Lamarck, 1804)	-0.29	-0.44	-0.32
Undetermined milioloids	-0.34	-0.47	0.53

which exceeded 25 psu. A salinity increase resulted in strong decrease in *C. poeyanum* abundance. This shift might have been caused by prolonged drought period and an overlap of prolonged negative phases of AMO and of ENSO which occurred during the time of a few decades. The latter indices in their negative phases result in the Florida and Florida Bay precipitation decrease and drier conditions (Enfield et al., 2001; Briceno and Boyer, 2010).

The hiatus at ~65 cm b.s.f. between ca. 200 BCE and the first half of the 19th century (Fig. 4) could potentially either be a result of an extreme weather event and associated sediment erosion by shifting currents coupled with potential change in the Marquesas Keys topography enabling a flow through the Mooney Harbor lagoon. This event most likely also uprooted existing SAV within the lagoon, which took

time to regrow once conditions within the lagoon stabilized. Slow regrowth of SAV communities slowly stabilized sediments which facilitated development of denser SAV communities. The effect of the extreme event was reflected by the lowest content of epiphytic foraminifera and low TOC content in sediment.

The shift from FA1 to FA3 at ca. 1939 CE (Fig. 4) corresponds with the reconstructed record of ocean-atmosphere teleconnections expressed by prolonged negative PDSI and ENSO phases predating 1939 CE and strong negative NAO phase after 1939 CE. The sediments predating 1939 CE show overall low accumulation rates oscillating around 1 mm/year. As shown in Fig. 4 the sediments dominated by FA1 are characterized by low TN and TP concentrations, and relatively high DIC. Environmental conditions typical for FA1 appear to be potentially long lasting, prevailing possibly since 2.5 thousand years ago, perhaps typical for the late Holocene and lasting until the early 20th Century.

5.1.2. FA2

FA2 dominates the most recent sediments (Fig. 4). Its occurrence is dated to 1990–2010 CE. Another interval of subordinate importance of FA2 at 53 cm b.s.f., with a brief dominance of this FA in the sample 48–49 cm b.s.f. dated at ca. 1872 CE. The abundance of the FA2 plotted against the core depth show max. ca. 20–30% during 1990–2010 CE and 1920–1930 CE, with ca. 20% at 1872 CE. In FA2 of the core top accumulation rates is the highest for the core studied and ranges from ca. 3 to 5 mm/year. In the uppermost part of the section, dominated by FA2, IC shows slight increase from 8 to 9%, whereas TOC, TN and TP decrease. Shift from FA3 to FA2 coincides with combination of prolonged strong negative phases of PDSI, ENSO and AMO, but with positive NAO phase that took place shortly before and after 1990 CE.

The FA2 assemblage, elevated in the 1860's to 1870's and dominating in the uppermost core interval dated to 1990–2010 CE, includes epiphytic species *M. circularis*, *R. floridana*, and *H. earlandi* which are associated with seagrass and the presence of phytodetritus (Brasier, 1975; Ishman, 2000; Collins et al., 2019). A shift to FA2 assemblage dated to ca. 1990 CE corresponds to short but strong PDSI negative phase and short negative phase of ENSO, whereas the episodic dominance of FA2 ca. 1872 CE corresponds to prolonged negative phases of ENSO and NAO. This community may have developed as the physical environment became less exposed to high energy ocean waves and more lagoonal in character allowing dense SAV communities to develop. However, following shift to FA1 and later to FA2 may indicate that lagoon formation was not a single event. High percentages of *Quinqueloculina* in FA2 are interpreted as indication of increased salinity (Murray, 1991; Brewster-Wingard and Ishman, 1999). The conditions are interpreted as typical for backreef, lagoonal habitats with dense SAV communities and normal to hypersaline conditions. During domination of FA2 in the topmost sediments (1990–2010 CE) we noted progressive reduction in nutrients, especially TN, but also TP though to a lesser extent (Fig. 3) and TOC but an increase in DIC and manyfold increase in accumulation rates. Interestingly several species of epiphytic foraminifera occur throughout the Marquesas core, but they reach elevated abundances in the uppermost part of the core corresponding to FA2 and FA3 assemblages. Their highest abundances correspond to the core part representing period between 1939 and 2010 CE, which is characterized by the highest sediment accumulation rates. There is a significant decrease (ca. 10%) in ephytic taxa abundance dated to late 1980' which corresponds to the period of seagrass die-off in the neighboring Florida Bay (Zieman et al., 1999; Hall et al., 2016; Collins et al., 2019). This implies that seagrass die-offs may have co-occurred in the study area. The epiphytic foraminifera abundance increased to 25% in the samples from the 1990 CE–2010 CE period, which implies increase in density of the SAV communities in the Marquesas Keys lagoon during that period (Fig. 4).

5.1.3. FA3

FA3 dominates between 8 and 18 cm b.s.f. in the sediment dated to



Fig. 5. Images of foraminifera from the studied core. a: *Pseudotriloculina linneiana*; b, c(?): *Quinqueloculina poeyanum*; d, e: *Miliolinella circularis*; f, f', g, g': *Rosalina floridana* (f, g' dorsal view); h, i: *Quinqueloculina candeiiana*; j: *Quinqueloculina laevigata*; k-m: *Quinqueloculina bosciiana*.

1939–1990 CE. In the remaining parts of the core, taxa indicative of FA3 reach low abundances (Fig. 4). The sediment dated to 1939–2010 CE, dominated by FA3 and FA2, shows strong increase in foraminifera diversity and abundance as well as decreased IC and elevated TOC, TN and TP (Fig. 3). The accumulation rate is also elevated up to 2–3 mm/year in the FA3. A shift from FA1 to FA3 coincides with negative phases of PDSI and ENSO and strongly positive AMO shortly before 1940 CE and a negative NAO index shortly after 1940 CE.

The FA3 assemblage, dominating in the intermediate core interval dated between 1939 and 1990 CE is dominated by *Q. poeyana*, *Q. bosciiana* and an unidentified juvenile *Quinqueloculina*. Domination of *Quinqueloculina* species may suggest high salinity conditions (Murray, 1991). Although *Q. poeyana*, similarly to *Q. laevigata* from FA2, is also known for its tolerance to episodic salinity decreases (Brasier, 1975). Thus, we interpret FA3 as typical for conditions similar for FA2, but less stable. Reconstructed ocean-atmosphere teleconnections indices show periods of negative phases of ENSO and even more distinct long negative phases of AMO and corresponding with them prolonged droughts periods (PSDI). Analysis of AMO index record shows period of 1940 to 1960's AD multiyear changes with strong positive phases and relatively

weak negative phases. During the time interval dominated by FA3 a significant switch from prevailing positive to a strong negative AMO phase was observed ~1960 CE. This has resulted in negative phases of PDSI and droughts. Additionally, historical hurricane records show two major hurricanes – a category 2 Hurricane Inez and category 1 Hurricane Floyd crossing the Marquesas Keys region in 1968 and 1987, respectively (<https://coast.noaa.gov/hurricanes/#map>).

In the interval dominated by FA3, significant shifts in DIC and DOC were observed, with the former strongly decreasing and the latter one increasing. These shifts were accompanied by changes in TN, which oscillations were most likely related to decomposition (mineralization) of the SAV material in the sediments (Holmer et al., 2001). Similar conditions were also recorded by Brewster-Wingard and Ishman (1999) in the central part of Florida Bay. Short periods of reduced salinity and brackish-water conditions were inferred for 1920–1940 CE and 1960–1980 CE, followed by increased salinity (>25) in 1940–1960 and 1980–1990 CE. Such changes in salinity within Florida Bay were caused by hurricanes and increased precipitation (refreshening) on one hand and salinity increase due to droughts on the other (Brewster-Wingard and Ishman, 1999). Cheng et al. (2012) referred to periodical changes in

salinity in the Florida Bay due to water management and related water supply projects. Characteristics of the FA3 indicate that the interval between 1939 and 1990 CE in the Marquesas Keys was characterized by salinity fluctuations influenced by droughts and hurricanes. Termination of FA3 is sudden and dated to 1990 CE, and corresponds to the well-documented 1987–1989 seagrass die-off in Florida Bay (e.g. Blum et al., 1988; Fourqurean and Robblee, 1999).

6. Conclusions

Analysis of a sediment core collected from Mooney Harbor in the Marquesas Keys revealed changes in foraminifera assemblages dated to 1990 CE, 1939 CE, and 1872 CE. These dates mark the appearances of distinct foraminifera assemblages which signify the occurrence of three stages of environmental change. Foraminifera assemblage (FA1) dominates in the lowermost part of the core between ca. 500 BCE and 1939 CE with a short appearance of FA2 dated to 1872 CE. FA1 is characterized by low diversity and composed of taxa typical for marginal marine environments. At 1939 CE FA1 is permanently replaced by FA3 composed of taxa typical of hypersaline environments. At 1990 CE FA 3 is replaced by FA2 and epiphytic taxa typical of seagrass communities. We interpret the environmental changes as caused by variation in precipitation patterns in the eastern Gulf of Mexico region associated with shifts in the major ocean-atmosphere teleconnections such as ENSO, AMO, NAO along with hurricanes. A well-developed epiphytic assemblage was recorded in the uppermost part of the studied core and dated to 1990–2010 CE implying the occurrence of the submerged aquatic vegetation within the Marquesas Keys Mooney Harbor. Consistent with the remote location of the Marquesas Keys, direct and significant impacts of anthropogenic factors were not evident in the study area.

Declaration of Competing Interest

The Authors declare no conflict of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.seares.2023.102451>.

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