

# Recent history of sediment deposition in marl- and sand-based marshes of Belize, Central America

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## Abstract

There are two contrasting types of wetlands in Belize: marl- and sand-based marshes. We measured accumulation rates of sediment in six cores from marl- and sand-based marshes of northern Belize and compared biogeochemical characteristics to assess recent wetland history (~ 1850 to present). Sediment depth increments were analysed for bulk density, LOI, nutrients (C, N, P, S, Ca, Mg, K and Na) and snail shell density and species diversity. Cores were dated using  $^{210}\text{Pb}$  and a constant rate of supply model. Unsupported  $^{210}\text{Pb}$  inventories of the cores ranged from 6.16 to 8.92  $\text{pCi cm}^{-2}$ . Marl-based marshes showed the maximum peak of  $^{210}\text{Pb}$  activity from 4 to 10 cm below the sediment surface.  $^{210}\text{Pb}$  peaks corresponded with the bottom of a marl layer containing chlorophyll *a* and we suggest that this relationship reflects the high growth and decomposition rates of cyanobacterial mat. Inorganic carbon, Ca, Mg, K, Na, S and Pb contents and accumulation rates were much greater in the marl-based marshes than in the sand-based marshes. Average dry mass accumulation rates in the six marshes ranged from 113 to 572  $\text{g m}^{-2} \text{ year}^{-1}$  over the past 100 years. Average linear sedimentation rates during the last 100 years in the two types were not significantly different (0.93 and 1.08  $\text{mm year}^{-1}$ , respectively). Increased sediment accumulation by human activities such as soil washout from adjacent roads was recorded in a sand-based marsh near roads. Sediment cores in the marl-based marshes display changes of marsh vegetation, apparently caused by water level changes. The vegetation change occurred at the end of the 1800s and the beginning of 1900s and is represented by a band of dark peat in otherwise marl-dominated sediments. Overall, the sediment cores show that conditions were relatively undisturbed by human activities in the recent past. © 2002 Elsevier Science B.V. All rights reserved.

**Keywords:** Belize;  $^{210}\text{Pb}$  dating; Marl; Sediment chemistry; Sedimentation; Water level change

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## 1. Introduction

Recent paleoecological and archaeological researches indicate that lowland humid regions of Meso-America were as important as highland areas for development of early human societies (Pohl et al., 1996; Fedick, 1996). Wetland agriculture in the Mayan Lowlands, specifically in Belize, has been well documented (Pohl, 1990; Jacob, 1995; Pope et al., 1996; Alcala-Herrera et al., 1994). Starting about 2500 BC, northern Belize was rapidly deforested, and the Mayan people probably settled around swamp margins where they found abundant plant, faunal and water resources (Pohl et al., 1996). By ca. 1000 BC, a rise in groundwater levels led farmers to construct drainage ditches. By the Classic period, AD 1–1000, wetland fields were flooded and mostly abandoned. The collapse of the Mayan civilization resulted in a substantial decrease in population density and consequently in less human impact on the ecosystem. For several centuries, the wetland ecosystems were influenced predominantly by natural processes until the middle of the 19th century, when sugarcane cultivation began in northern Belize.

Sediment cores from the Mayan Lowlands have indicated processes and events that occurred centuries and millennia BP (Jacob, 1995; Pohl et al., 1996). Northern Belize provides an opportunity to compare the sediment histories of calcareous, sulfate-rich marl-based marshes with noncalcareous, sulfate-poor, sand-based wetland ecosystems in an otherwise climatically uniform area (Rejmánková and Post, 1996). Differences in sediment chemistry and accumulation rates reflect differences in water sources (precipitation vs. groundwater discharge), biological activity (presence vs. absence of cyanobacterial mats and macrophyte species) and anthropogenic impacts. The goal of this study was to compare sedimentation rates in the two different types of marshes. Two hypotheses were tested:

- (1) There is a higher accumulation rate of cations and inorganic carbon in marl-based marshes primarily through chemical precipitation.
- (2) Sediment accumulation rates are higher in marshes exposed to allochthonous input by human activities such as soil washout from adjacent roads.

We (1) measured organic matter, nutrient concentrations (C, N, P) and other elements (Ca, Mg, K, Na, Pb) in sediments, (2) determined recent sediment accumulation rates by  $^{210}\text{Pb}$  dating and (3) evaluated relative mollusc abundance as possible indicators of environmental change. In addition, we analysed top sediment layers from the marl-based marshes for chlorophyll *a* to document the depth of the live epipelonal layer.

## 2. Study Area

Belize is located on the southeastern part of the Yucatan peninsula (Fig. 1). It is sparsely inhabited but archaeological data indicate the region had higher population densities in the past. More than 30% of the country is represented by low-lying coastal plains; the remainder is hilly and mountainous. The lowlands include a range of relatively undisturbed wetland ecosystems (Rejmánková et al., 1996). The northern coastal region is

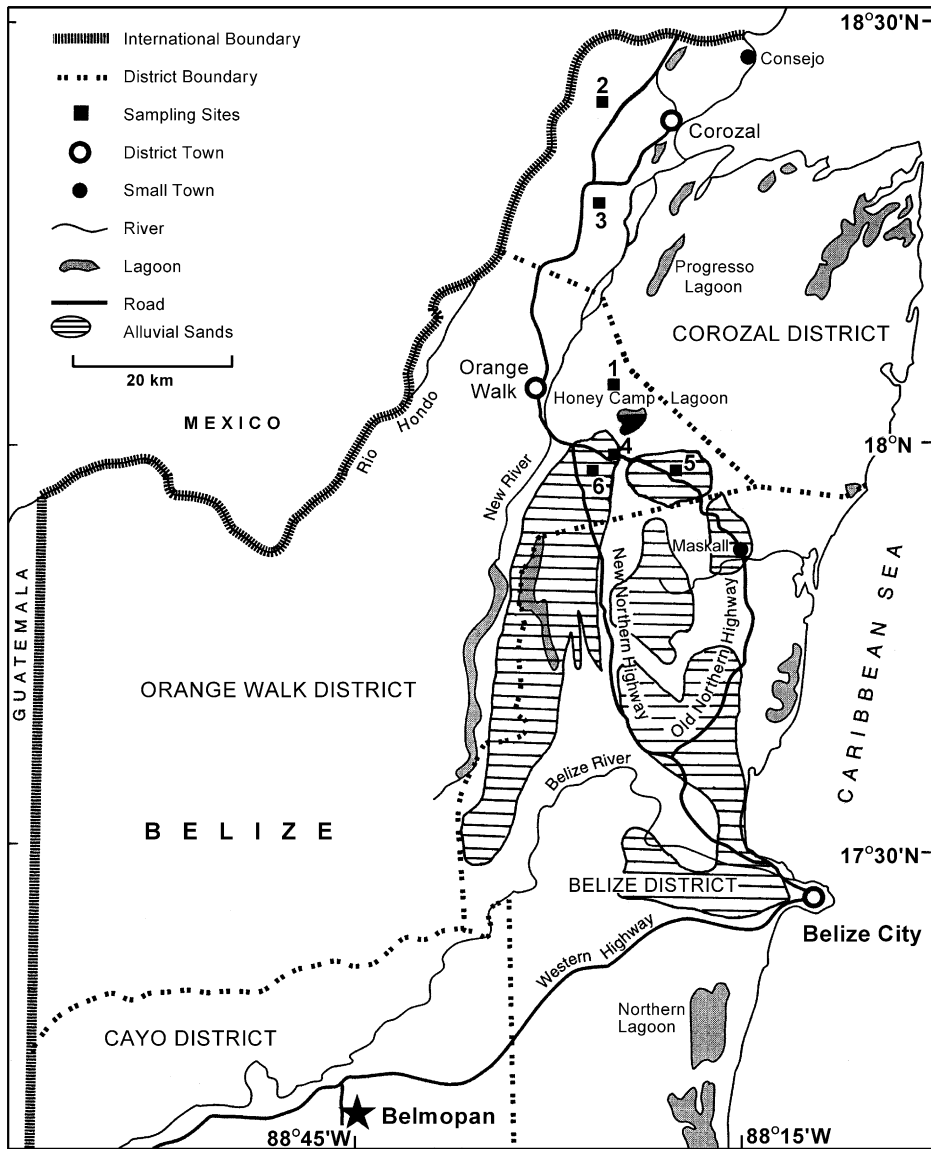


Fig. 1. Location of the study sites in northern Belize. Marl-based marshes: (1) Doubloon, (2) Chan Chen, (3) Buena Vista. Sand-based marshes: (4) Big Snail, (5) ONH, (6) ONH11.

drained primarily by three river systems: the Rio Hondo, the New River and the Northern River (Fig. 1). Surface and subsurface drainage patterns are quite complex. Waterlogged areas support several types of swamp forest, both freshwater and mangroves. Numerous herbaceous marshes are dominated by tall emergent sawgrass (*Cladium jamaicense*), rushes (*Eleocharis cellulosa*, *E. interstincta*) and cattails (*Typha domingensis*) with

subdominants of both floating and submerged aquatic macrophytes (Rejmánková et al., 1996). Marshes on limestone frequently contain cyanobacterial mats consisting mostly of fine filaments of the genus *Leptolyngbya* intermingled with other cyanobacterial species (Rejmánková and Komárková, 2000).

Following the collapse of the Classic Maya in the 9th century AD, agriculture was rather sparse in Belize until the mid-19th century. Sugarcane cultivation was established in the 1850s but most of its development has occurred during the last 30 years. It is now the most important cash crop in Belize, with some 30,000 ha cultivated by 1987 (King et al., 1992).

### 3. Methods

#### 3.1. Core sampling

Sediment cores were collected from three marshes (Doubloon, Chan Chen and Buena Vista) in the marl-based area and three (Big Snail, ONH and ONH11) in the sand-based area (Fig. 1). These six wetlands represent the range of size, water depth, water chemistry and macrophyte density (Table 1) occurring in the *E. cellulosa*-dominated marshes of northern Belize (Rejmánková et al., 1996). The extensive sands probably originate from weathering of granitic parts of the Maya Mountains during the Pleistocene (Wright et al., 1959).

One core was collected in each marsh in March 1998 by driving a plastic open-end sampler (5.6 cm inside diameter) to a depth of 50 cm. The upper end of the corer was then capped and the other end was capped after retrieval. Cores were transported to the laboratory and preserved in a freezer. In addition, shorter cores spanning the upper ~ 15 cm of the sediment profile were collected from the marl-based marshes in March 1999 for

Table 1  
Environmental characteristics of the study sites

	Base	Area (ha)	Water depth (cm)		Water conductivity (mS cm <sup>-1</sup> )	Dominant vegetation
			Average	Range		
Doubloon	Limestone	65	17	0–85	5.50	sparse <i>Eleocharis cellulosa</i> , cyanobacterial mats
Chan Chen	Limestone	78	34	0–90	3.42	sparse <i>Eleocharis cellulosa</i> , cyanobacterial mats
Buena Vista	Limestone	75	22	0–49	2.07	sparse <i>Eleocharis cellulosa</i> , cyanobacterial mats
Big Snail	Sand	50	42	0–89	0.45	<i>Eleocharis interstincta</i> , some cyanobacterial mats
ONH	Sand	8	30	0–45	0.25	<i>Eleocharis interstincta</i> , no cyanobacterial mats
ONH11	Sand	8	30	0–60	0.08	<i>Eleocharis interstincta</i> , no cyanobacterial mats

Doubloon and Chan Chen are parts of larger marsh/lagoon complexes and the area shown here applies to a homogeneous part of the marsh.

chlorophyll *a* analyses. These cores were frozen and sectioned into 1-cm layers. Half of the fresh samples collected in 1998 was used for mollusc analysis and others were air-dried and ground with a mortar and a pestle and sieved through a 250- $\mu\text{m}$  stainless steel screen for  $^{210}\text{Pb}$  dating and physical and chemical analyses. Two or three dry samples were combined if 1-cm thick samples were not enough for chemical and  $^{210}\text{Pb}$  analyses. Alternate samples were analysed chemically, but intervening samples were analysed when it was difficult to interpolate results between data points.

### 3.2. Mollusc counting

Half of each sediment sample ( $12.5\text{ cm}^3$ ) was wet sieved with a 250- $\mu\text{m}$  sieve and dried at  $105^\circ\text{C}$  to count mollusc shells. Intact shells  $> 1\text{ mm}$  were sorted, identified and counted following Covich (1976, 1983) and Taylor (1966).

### 3.3. $^{210}\text{Pb}$ dating

$^{210}\text{Pb}$  activity was measured by alpha spectrometry following Kim and Rejmánková (2001) based on a modification of the Smith and Hamilton (1984) and Binford (1990) methods. Supported  $^{210}\text{Pb}$  was estimated from total  $^{210}\text{Pb}$  by assuming that the background activity of total  $^{210}\text{Pb}$  in the bottom portion of cores represented supported  $^{210}\text{Pb}$  (Binford, 1990; Craft and Richardson, 1993). Cores were  $^{210}\text{Pb}$  dated using a constant rate of supply (CRS) model (Appleby and Oldfield, 1978; Binford, 1990). Dry mass accumulation rates were calculated according to Binford (1990).  $^{210}\text{Pb}$  dates were used to calculate average sediment accumulation rates for the past 150 years. Marl-based marshes had an upper marl layer mixed with live cyanobacteria and  $^{210}\text{Pb}$  activity increased with depth to maxima at 4, 10 and 8 cm in the Doubloon, Chan Chen and Buena Vista cores, respectively.  $^{210}\text{Pb}$  dates corresponding to these depths instead of the sample collection year were used at these sites as upper points for the calculation of average sediment accumulation rates.

### 3.4. Physical and chemical analyses

Moisture content of air-dried sediments was determined after drying at  $105^\circ\text{C}$  for 24 h. Bulk density was calculated as dry weight per wet volume and loss on ignition was determined by combustion in a muffle furnace at  $550^\circ\text{C}$  for 4 h (Dean, 1974). Total carbon (TC), nitrogen (N) and inorganic carbon (IC) were determined on a Carlo-Erba series 5000 CHN-S analyzer. The ash after ignition was used for the determination of IC (Kim and Rejmánková, 2001). Delta  $^{13}\text{C}$  values of air dried sediments were determined by Isotope Ratio Mass Spectrometer (Europa Integra-CN, DPZ Europa). Total phosphorus (P), sulfur (S) and lead (Pb) were determined by ICP-AES (Inductively Coupled Plasma spectroscopy, Thermo Jarrell Ash, model Atom Scan 25) after microwave acid digestion (Sah and Miller, 1992). The digested solution was also used to determine total sodium (Na), potassium (K), calcium (Ca) and magnesium (Mg) with a Perkin-Elmer 2380 Atomic Absorption Spectrophotometer following Allen (1989). Sulfate-sulfur ( $\text{SO}_4\text{-S}$ ) was determined by ICP-AES (Meyer and Keliher, 1992) after extraction with monocalcium phosphate (Schulte and Eik, 1988).

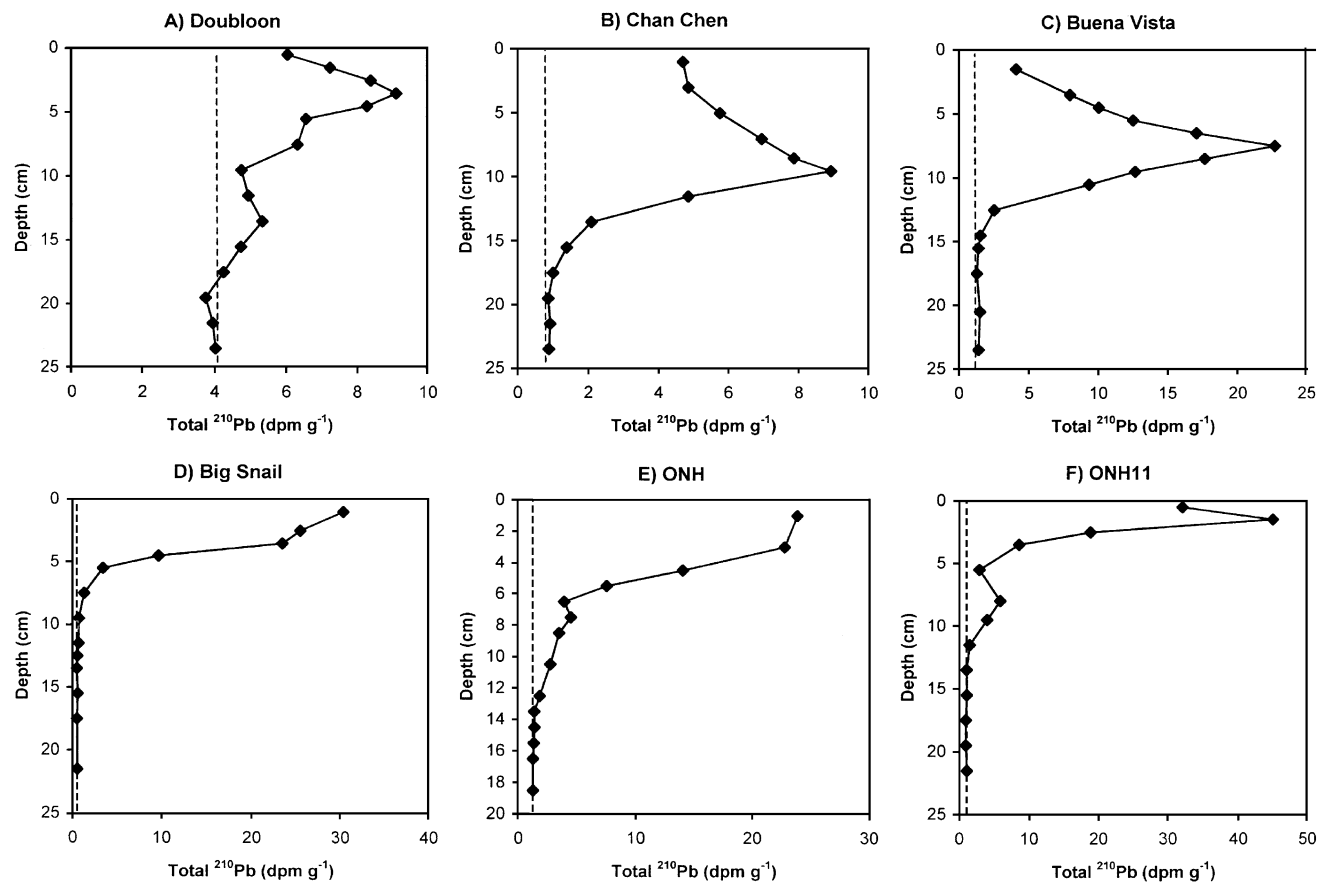


Fig. 2. Total  $^{210}\text{Pb}$  depth profiles in Belizean cores. Marl-based marshes: (A) Doublloon, (B) Chan Chen, (C) Buena Vista. Sand-based marshes: (D) Big Snail, (E) ONH, (F) ONH11. Dotted lines indicate supported  $^{210}\text{Pb}$ .

### 3.5. Chlorophyll *a* analysis

Chlorophyll *a* was extracted from 0.5 g fresh sediment samples with 20 ml methanol for 24 h in a refrigerator (Hunter et al., 1993). Chlorophyll *a* in the supernatant was determined with a fluorometer (Turner Quantech, model FM 109525) at 440 nm excitation and 665 nm emission wavelengths. To correct for the presence of phaeophytin pigments (degradation products of chlorophyll *a*), a drop of 6 N HCl was added and fluorescence was determined again. Chlorophyll *a* was calculated as follows:

$$\text{chlorophyll } a[\text{g/g}] = (F_a - F_b) \times (\text{Evol/wt}) \times k \times (R/(R - 1)) \quad (1)$$

where  $F_a$  is the initial fluorometer reading,  $F_b$  is the second (postacidification) fluorometer reading,  $k$  is a calibration factor (0.0661), Evol is the volume of extraction solvent and  $R$  is the ratio of absorbency before and after acidification (for methanol,  $R = 3.9326$ ).

### 3.6. Data analysis

StatView for Windows (Abacus Concepts, Version 4.57) was used for statistical analysis. Detrended canonical correspondence analysis (DCA) was performed using CANOCO for Windows (GLW-CPRO, Version 4.0), which is a program for classifying objects according to their measured properties. This was used to group the marshes objectively, based on 13 physical and chemical sediment characteristics.

## 4. Results

### 4.1. Radioisotope chronology

Supported  $^{210}\text{Pb}$  activities were reached at depths in the six cores ranging from 13 to 19 cm:  $1.69 \pm 0.06$ ,  $0.40 \pm 0.01$ ,  $0.62 \pm 0.04$ ,  $0.25 \pm 0.02$ ,  $0.57 \pm 0.01$  and  $0.47 \pm 0.03$

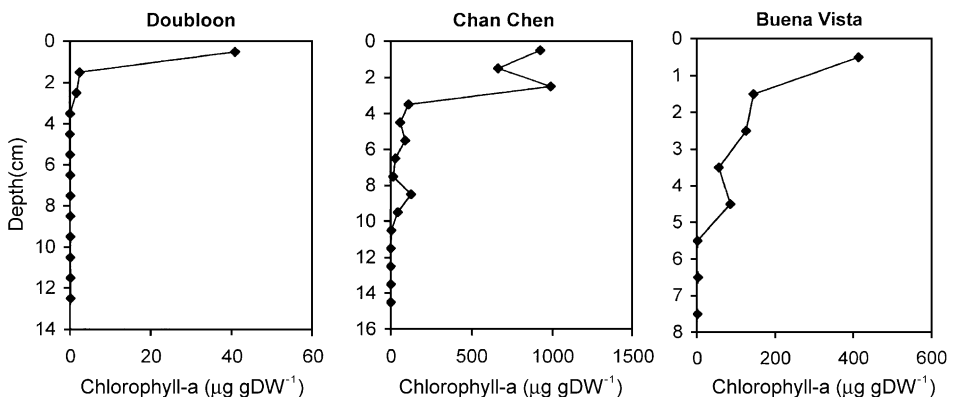
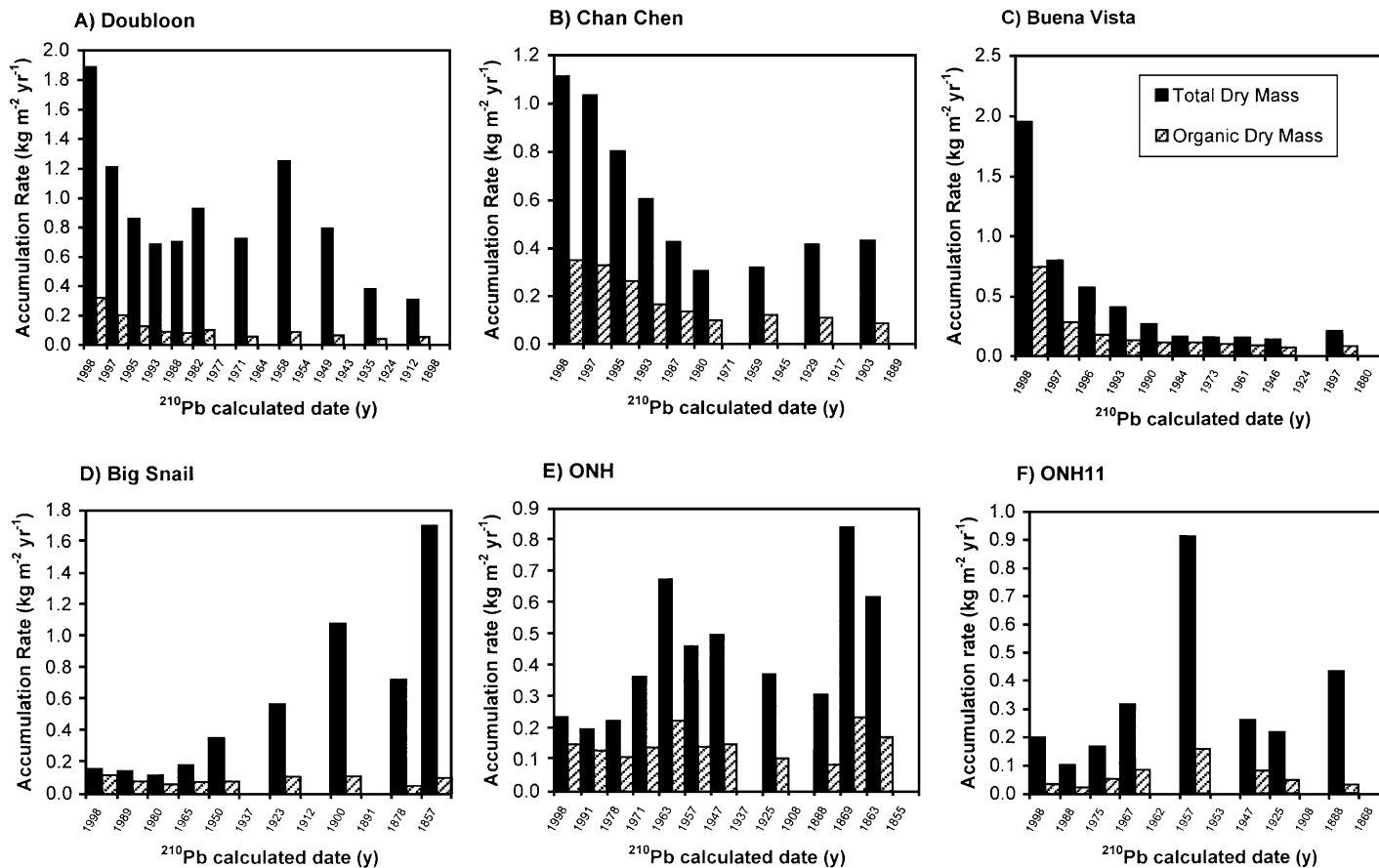


Fig. 3. Chlorophyll *a* depth profiles in Doubloon, Chan Chen and Buena Vista cores. gDW: gram dry weight.

Fig. 4. Sediment accumulation rates and  $^{210}\text{Pb}$  dates in Belizean cores.



pCi/g in Doubloon, Chan Chen, Buena Vista, Big Snail, ONH and ONH11, respectively. The trends of unsupported  $^{210}\text{Pb}$  activity with increasing depth reveal two patterns (Fig. 2): sand-based marshes with decreasing curves except for small peaks in mid core; and marl-based marshes with first increasing and then decreasing curves. However, the sand-based marshes showed significant departures from simple monotonic decline, possibly reflecting episodic variations in the sedimentation rate. Maximum  $^{210}\text{Pb}$  activities in Doubloon, Chan Chen and Buena Vista occurred at depths of 4, 10 and 8 cm, respectively. The chlorophyll *a* analyses indicated that only sediment layers from the top to the depth of maximum  $^{210}\text{Pb}$  activity contain chlorophyll *a*. Chlorophyll *a* concentration decreased to near zero at 4, 11 and 6 cm in Doubloon, Chan Chen and Buena Vista, respectively (Fig. 3). Rejmánková and Komárková (2000) observed live benthic cyanobacterial mats (epipelon) in this layer. Below these depths,  $^{210}\text{Pb}$  activities in Chan Chen and Buena Vista decline exponentially with depth. All cores had similar unsupported  $^{210}\text{Pb}$  inventories: 6.29, 6.16, 7.72, 6.84, 7.75 and 8.92 pCi/cm<sup>2</sup> in Doubloon, Chan Chen, Buena Vista, Big Snail, ONH and ONH11, respectively, that yielded corresponding  $^{210}\text{Pb}$  flux rates of 0.20, 0.19, 0.24, 0.21, 0.24 and 0.28 pCi cm<sup>-2</sup> year<sup>-1</sup>. The mean value of 7.28 pCi/cm<sup>2</sup> reflects a  $^{210}\text{Pb}$  supply rate of 0.23 pCi cm<sup>-2</sup> year<sup>-1</sup> in northern Belize.

#### 4.2. Dry mass accumulation rate changes

Total dry mass accumulation rate in Doubloon increased until about 1958, then stayed around 0.8 kg m<sup>-2</sup> year<sup>-1</sup>, but increased after ~ 1993 (Fig. 4). In Chan Chen and Buena Vista, they increased after the 1980s and 1990s, respectively. In sand-based marshes, they were high (~ 0.9 kg m<sup>-2</sup> year<sup>-1</sup>) in the late 1800s and those in ONH and ONH11 increased around the 1950s.

#### 4.3. Average accumulation rates

Average total dry mass accumulation rate was highest (572.3 g m<sup>-2</sup> year<sup>-1</sup>) in Doubloon and lowest (112.7 g m<sup>-2</sup> year<sup>-1</sup>) in Buena Vista, but organic matter accumulation was least (57.3 g m<sup>-2</sup> year<sup>-1</sup>) in Doubloon and most (114.9 g m<sup>-2</sup> year<sup>-1</sup>) in ONH (Table 2). Mean dry mass accumulation rate (329.2 g m<sup>-2</sup> year<sup>-1</sup>) in marl-based marshes was similar to that (305.6 g m<sup>-2</sup> year<sup>-1</sup>) in sand-based marshes, but there were large differences among marl-based marshes, ranging from 111.7 to 572.3 g m<sup>-2</sup> year<sup>-1</sup>. Inorganic C, Ca, Mg, Na and S accumulation rates showed the same decreasing tendencies as water conductivity: highest in Doubloon and lowest in ONH11 (Table 1). In general, cations, S and IC accumulations in the marl-based marshes were greater than in the sand-based marshes; however, organic matter, OC, N and P accumulation rates were greater in the sand-based marshes than in the marl-based marshes.

#### 4.4. Physical and chemical characteristics

Sediment cores were composed of marl containing live cyanobacteria (epipelon), marl, peat and clay. A peaty layer occurred in the marl-based marshes at 18–15 cm (~ 1850 to

Table 2  
Recent accumulation rates in Belizean marshes

Period	Site	SR (mm yr <sup>-1</sup> )	TM (g m <sup>-2</sup> yr <sup>-1</sup> )	OM (g m <sup>-2</sup> yr <sup>-1</sup> )	Total C (g m <sup>-2</sup> yr <sup>-1</sup> )	IC (g m <sup>-2</sup> yr <sup>-1</sup> )	OC (g m <sup>-2</sup> yr <sup>-1</sup> )	Total N (g m <sup>-2</sup> yr <sup>-1</sup> )
1898–1993	DBL	1.4	572.3	57.3	86.2	57.3	28.9	2.1
1903–1987	CC	0.8	302.6	99.6	55.0	6.4	48.6	3.9
1897–1984	BV	0.6	112.7	60.9	33.2	0.8	32.4	2.4
Marl-based	Average	0.9	329.2	72.6	58.1	21.5	36.6	2.8
1900–1998	BS	0.9	272.1	73.0	39.9	0.1	39.8	3.6
1908–1998	ONH	1.2	319.0	114.9	56.0	0.1	55.9	4.5
1908–1988	ONH11	1.1	254.9	59.5	30.4	0.1	30.3	2.5
Sand-based	Average	1.1	282.0	82.5	42.1	0.1	42.0	3.5
Total	Average	1.0	305.6	77.5	50.1	10.8	39.3	3.2
Period	Site	Total P (mg m <sup>-2</sup> yr <sup>-1</sup> )	Total Ca (g m <sup>-2</sup> yr <sup>-1</sup> )	Total Mg (g m <sup>-2</sup> yr <sup>-1</sup> )	Total K (mg m <sup>-2</sup> yr <sup>-1</sup> )	Total Na (mg m <sup>-2</sup> yr <sup>-1</sup> )	Total S (g m <sup>-2</sup> yr <sup>-1</sup> )	Total Pb (mg m <sup>-2</sup> yr <sup>-1</sup> )
1898–1993	DBL	55.1	179.4	3.1	88.8	1097.8	4.7	28.4
1903–1987	C	86.8	18.9	2.9	1301.9	465.4	3.7	7.9
1897–1984	BV	35.5	4.3	0.6	236.5	145.7	1.4	2.6
Marl – based	Average	59.1	67.6	2.2	542.4	569.6	3.3	13.0
1900–1998	BS	37.5	2.1	0.4	80.3	25.3	0.6	2.7
1908–1998	ONH	41.6	3.2	0.2	123.8	26.1	1.0	7.8
1908–1988	ONH11	121.7	0.9	0.2	76.0	22.4	0.3	4.7
Sand-based	Average	66.9	2.0	0.3	93.4	24.6	0.6	5.0
Total	Average	63.0	34.8	1.2	317.9	297.1	2.0	9.0

DBL: Doubloon, CC: Chan Chen, BV: Buena Vista, BS: Big Snail. TM: total mass, OM: organic matter, IC: inorganic carbon, OC: organic carbon.

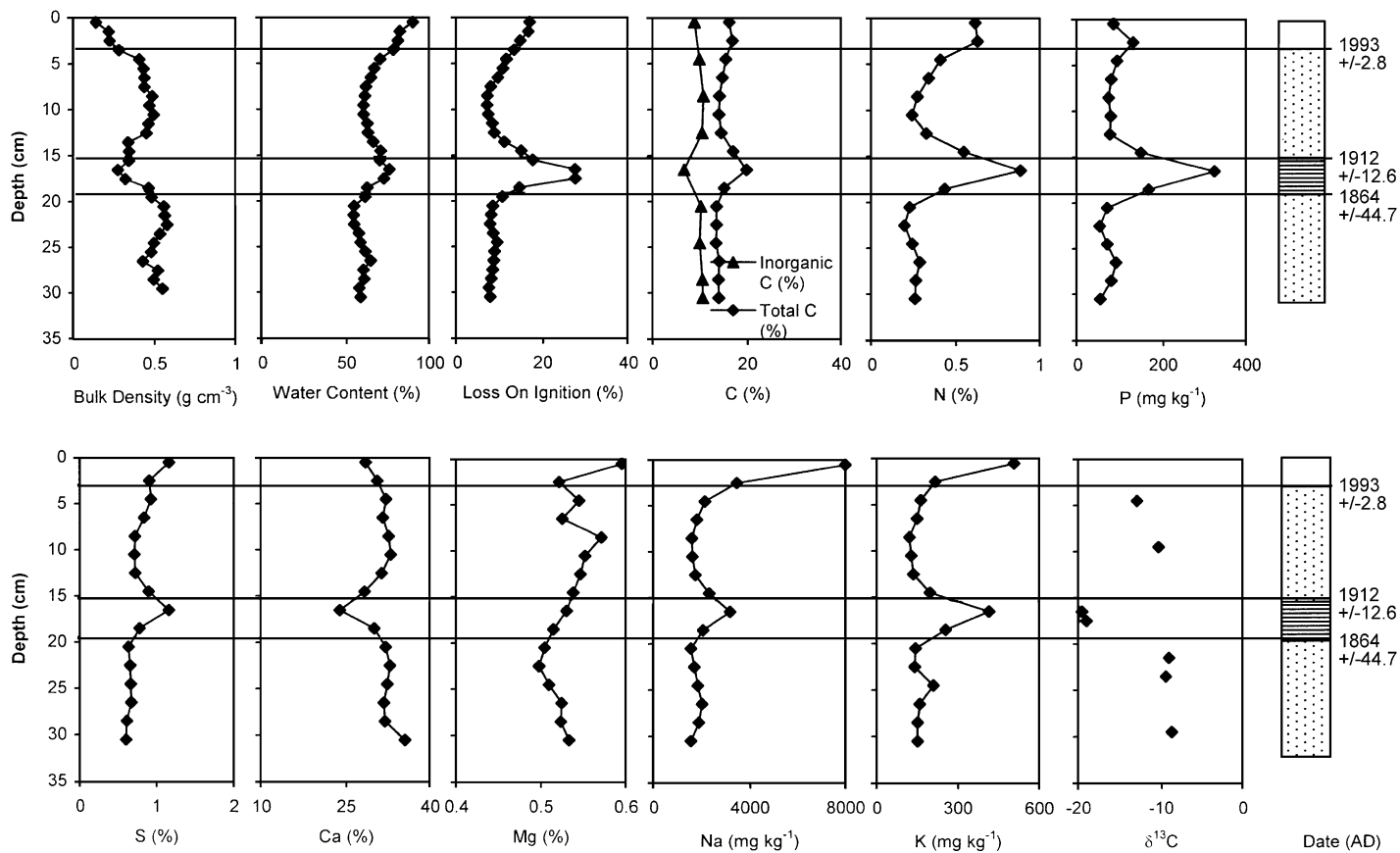


Fig. 5. Depth distributions of physical and chemical properties in the soil core collected from Doubloon. The sequence on the right indicates from top to bottom: marl containing live cyanobacteria, marl, peaty marl and marl.

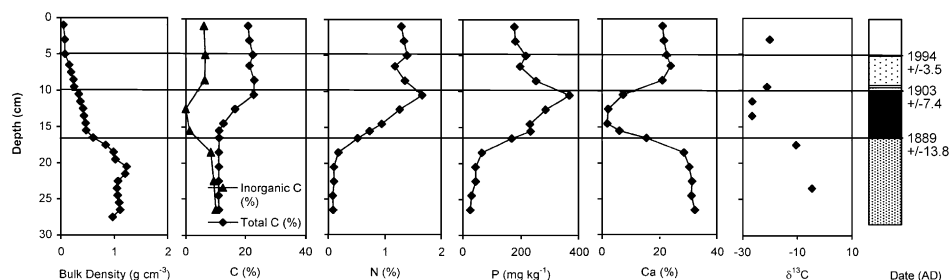


Fig. 6. Depth distribution of physical and chemical properties in the soil core collected from Chan Chen. The sequence on the right indicates from top to bottom: marl containing live cyanobacteria, marl, peaty marl, peat and silty marl.

1912) in Doubloon, 16–10 cm ( ~ 1889 to 1903) in Chan Chen and 14–7 cm ( ~ 1860 to 1984) in Buena Vista. In Doubloon, it had a distinctly different  $\delta^{13}\text{C}$  content (  $-19\text{‰}$  ) from the marl above and below (about  $-10\text{‰}$  ) (Fig. 5). Microscopic inspection showed that it is a mixture of marl and peat derived from *C. jamaicense*. The  $\delta^{13}\text{C}$  of plants and sediments recently surveyed in marshes of Belize were  $-27\text{‰}$  to  $-30\text{‰}$  for  $\text{C}_3$  emergent plants,  $-18\text{‰}$  for live cyanobacterial mat and  $-14\text{‰}$  to  $-10\text{‰}$  for marl sediment (E. Rejmánková, unpublished data). Assuming the peat component was derived only from  $\text{C}_3$  emergent plants, the  $\delta^{13}\text{C}$  content of the peat layer indicates 59% peat and 41% marl (calculation by two-box mixing model). The  $\delta^{13}\text{C}$  value of the peat layer at Chan Chen was  $-29\text{‰}$  (Fig. 6) and microscopic inspection indicated that this peat was also formed from herbaceous plants, mainly *C. jamaicense*.

The change in sediment type between 15- and 18-cm depths in Doubloon coincides with the change in other physical and chemical characteristics (Fig. 5). Bulk density was less (  $\sim 0.2 \text{ g m}^{-3}$  ) and water content, LOI, C, N, Na, S and K in peaty marl layer were greater than in the marl layer. Inorganic C in this peaty marl was 40% of TC, less than in the marl layers (about 65% of TC).

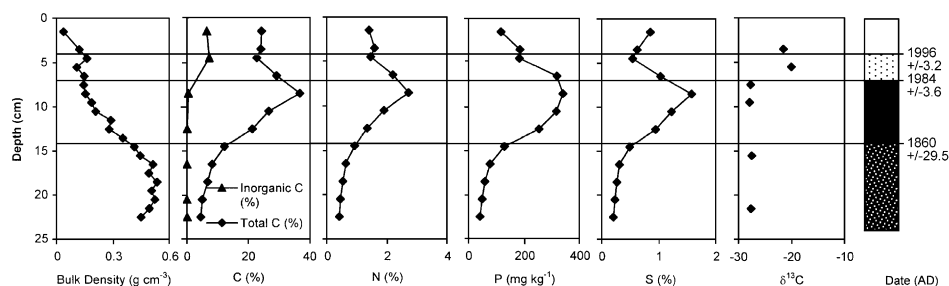


Fig. 7. Depth distribution of physical and chemical properties in the soil core collected from Buena Vista. The sequence on the right indicates from top to bottom: marl containing live cyanobacteria, marl, peat and peaty clay.

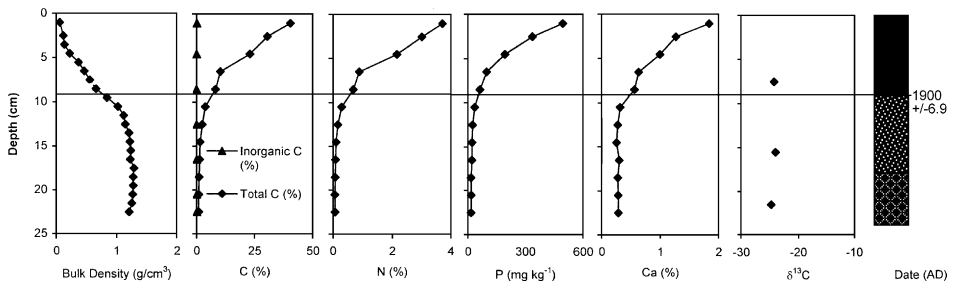


Fig. 8. Depth distribution of physical and chemical properties in the soil core collected from Big Snail. The sequence on the right indicates from top to bottom: peat, peaty clay and sandy clay.

The Chan Chen sediment was composed of marl containing live cyanobacteria, peat and silty marl (Fig. 6). Bulk density increased gradually with depth to 20 cm. LOI, OC, N and P contents were highest in the upper part of the peat and decreased with depth to 19 cm. Inorganic C content was 30% of TC in the upper marl layer, but decreased to 0.2% in the peat and increased to 90% of TC in the silty marl. The Ca content of the upper marl layer was 20% of total dry mass; it decreased to 2% in the peat layer, and increased to 30% in the lower silty marl layer. The S content (data not shown) of the upper marl layer was greater than in deeper silty marl, and decreased with increasing depth in the peat layer. Mg and K (data not shown) were most abundant in the middle of the peat layer.

The Buena Vista sediment consisted of marl containing live cyanobacteria, with a marl layer in the upper 7 cm and a peat layer below 7 cm formed in 1984 (Fig. 7). Bulk density increased with depth to 16 cm. The LOI, OC, N, P and S contents were largest in the upper part of the peat layer and decreased with depth. Inorganic C in the peat layer was very small (<1% of TC). The Ca content (data not shown) was greater in the upper marl layer than in lower peat layer. The P content was much greater in the peat than in the marl.

The Big Snail sediment consisted of peat, peaty clay and sandy clay (Fig. 8). Bulk density increased with depth to 10 cm (~1891) and all other physical and chemical variables except IC and Na (data not shown) decreased gradually to this depth. Inorganic C was very small (<1% of TC) and Na decreased to 5-cm depth.

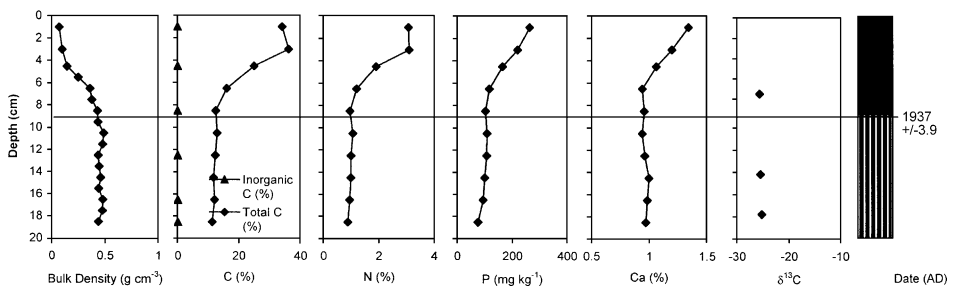


Fig. 9. Depth distribution of physical and chemical properties in the soil core collected from ONH. The sequence on the right indicates from top to bottom: peat and clay peat.

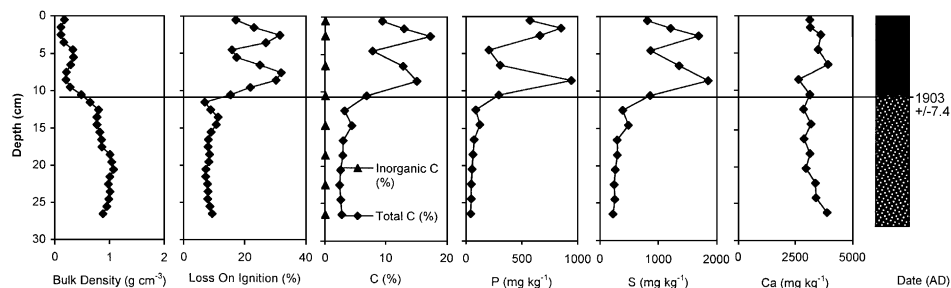


Fig. 10. Depth distribution of physical and chemical properties in the soil core collected from ONH11. The sequence on the right indicates from top to bottom: peat and peaty clay.

The ONH marsh core consisted of peat and clay. All the physical and chemical variables except bulk density decreased with depth to 11 cm (Fig. 9). Bulk density gradually increased with depth and remained at around  $0.45 \text{ g cm}^{-3}$  below 11 cm. Inorganic C content was negligible.

The ONH 11 marsh core consisted of peat and clay (Fig. 10). Bulk density increased with depth to 5 cm, decreased from 5 to 9 cm, and then increased with depth, but LOI, OC, N (data not shown), P and S contents all showed the opposite pattern.

Average bulk density and contents of IC, Ca, Mg, Na and S were greater in the marl-based marshes than in the sand-based marshes, but organic content was higher in sand-based marshes than in marl-based marshes (Table 3).

The average total lead contents in the Doubloon, Chan Chen and Buena Vista cores were 50, 47, 41 ppm in the marl layer and 45, 19, 20 ppm in the peaty marl or peat layer, respectively (Fig. 11). In the Big Snail core it was 7 ppm below 9-cm depth and the peak of 19.2 ppm appeared at the 2–3-cm depth. In the ONH core, it was ca. 24

Table 3  
Physical and chemical properties of Belizean marsh sediments

	Doubloon	Chan Chen	Buena Vista	Big Snail	ONH	ONH11
Water content (%)	66 (10)	62 (23)	74 (14)	48 (260)	57 (22)	69 (14)
Bulk density ( $\text{g cm}^{-3}$ )	0.421 (0.123)	0.559 (0.421)	0.294 (0.179)	0.825 (0.486)	0.602 (0.367)	0.343 (0.165)
LOI (%)	11.7 (5.5)	21.5 (13.0)	32.2 (15.6)	20.2 (24.1)	15.0 (8.5)	37.8 (15.6)
Organic C (%)	5.4 (2.8)	10.0 (6.8)	16.3 (9.8)	10.3 (13.5)	7.0 (5.2)	18.4 (9.7)
Inorganic C (%)	9.61 (1.12)	6.03 (3.30)	2.23 (3.14)	0.05 (0.07)	0.03 (0.01)	0.03 (0.01)
N (%)	0.39 (0.20)	0.81 (0.59)	1.30 (0.74)	0.94 (1.29)	0.61 (0.45)	1.51 (0.88)
P ( $\text{mg kg}^{-1}$ )	106 (68)	168 (104)	172 (112)	111 (155)	291 (312)	135 (62)
Ca (%)	30.9 (2.4)	19.7 (10.7)	8.0 (9.1)	0.6 (0.5)	0.3 (0.04)	1.0 (0.1)
Mg ( $\text{mg kg}^{-1}$ )	5331 (258)	7198 (1917)	6013 (949)	1134 (542)	843 (107)	776 (128)
K ( $\text{mg kg}^{-1}$ )	205 (112)	2075 (1817)	1627 (1058)	259 (103)	261 (177)	371 (48)
Na ( $\text{mg kg}^{-1}$ )	2453 (1628)	1733 (1057)	1271 (235)	108 (187)	101 (123)	82 (27)
S ( $\text{mg kg}^{-1}$ )	8082 (1770)	10647 (5354)	6918 (4394)	1577 (2075)	737 (557)	3297 (1856)
Pb ( $\text{mg kg}^{-1}$ )	49.2 (1.8)	40.3 (10.8)	27.7 (10.1)	9.5 (3.8)	16.5 (5.30)	23.4 (1.4)

Values in parentheses indicate  $1 \pm \text{S.D.}$  LOI=loss on ignition.

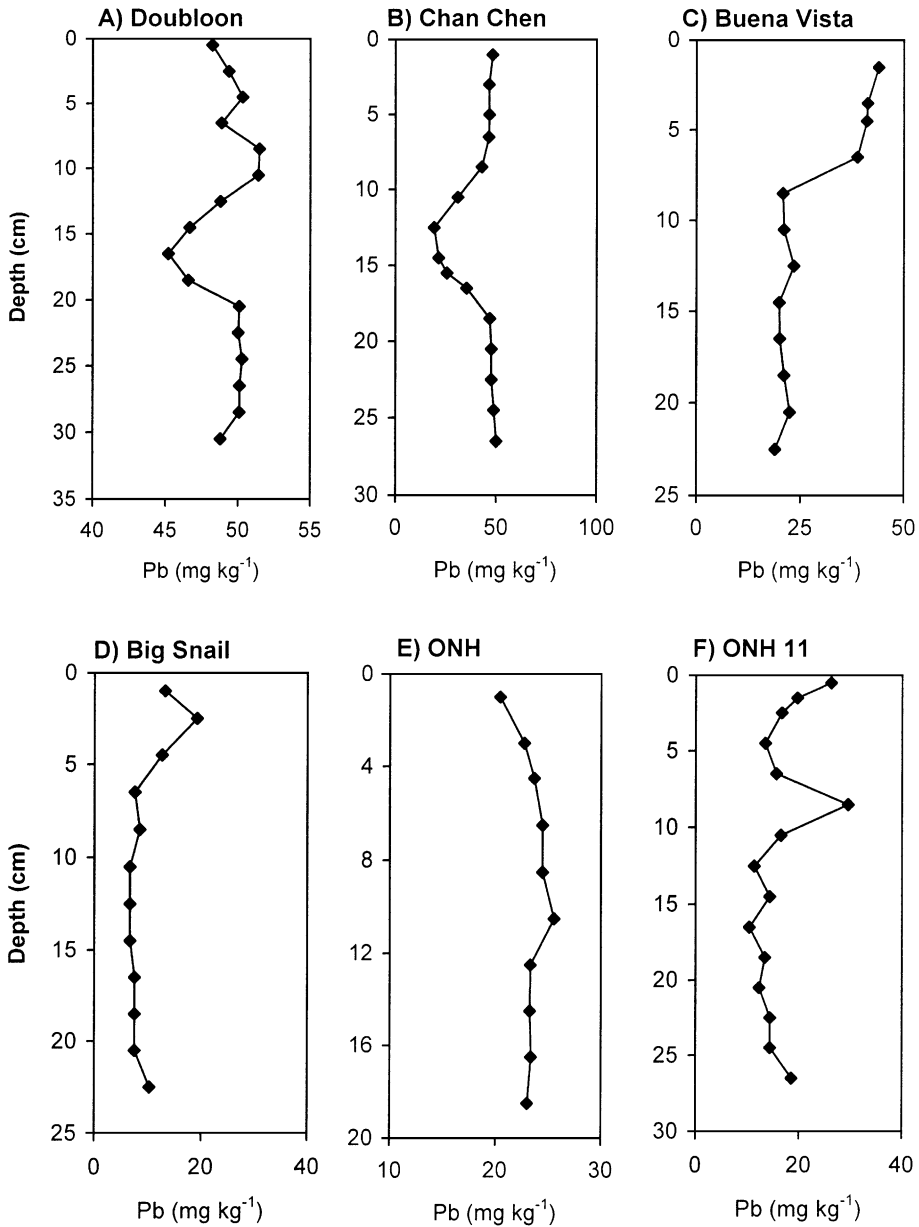


Fig. 11. Total lead depth profiles in the study sites.

ppm throughout, in the ONH11 core it was 12 ppm below 12 cm and showed peaks of 29.5 and 26.2 ppm at 9-cm depth and at the surface, respectively. In the Buena Vista, Big Snail and ONH11 cores, it increased upwards from depths equivalent to 1961,

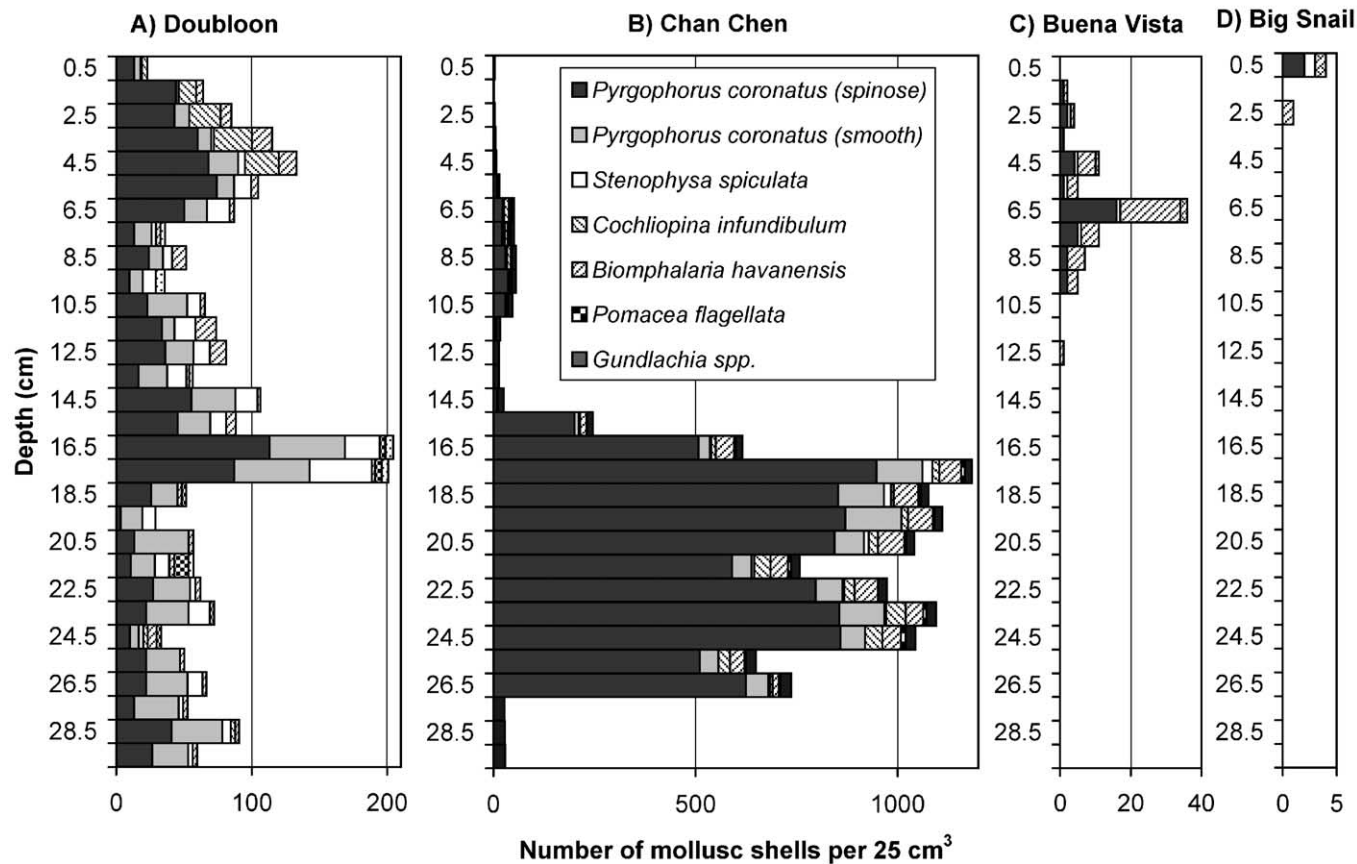


Fig. 12. Frequency distribution of molluscan species in the Doubloon, Chan Chen, Buena Vista and Big Snail marshes.



1950 and 1957, respectively; however, there is a peak at 9-cm depth (about 1923) in ONH11.

#### 4.5. Mollusc distribution

Mollusc shells were found in the Doubloon, Chan Chen, Buena Vista and Big Snail cores (Fig. 12). All the identified species were fresh water. They were most abundant in the Chan Chen core with 1091 shells per 25 cm<sup>3</sup> at 19–20-cm depth. There were two peaks of shell abundance in Doubloon at 16–19-cm depth (200 shells per 25 cm<sup>3</sup>) and 4–5-cm depth (130 shells per 25 cm<sup>3</sup>). About 1000 shells per 25 cm<sup>3</sup> were retrieved below 17-cm depth and relatively few shells occurred above 15-cm depth in the Chan Chen core. In the Buena Vista core, they occurred only in the upper 13 cm. A maximum of 36 shells per 25 cm<sup>3</sup> occurred at 6–7 cm in the Buena Vista core. Few mollusc shells were observed within the upper 3 cm in Big Snail.

The spinose form of *Pyrgophorus coronatus* was the most abundant species, contributing 50% of all shells identified. Most *Cochliopina infundibulum* shells were found in the upper 5 cm, and *Biomphalaria havanensis* increased above 12-cm depth. *Pomacea flagellata* shells occurred mainly at 16–25-cm depth. The spinose form of *P. coronatus* (about 58% of total shells) was more abundant in the Chan Chen core than in the Doubloon core. The distribution patterns of spinose and smooth forms of *P. coronatus* were similar in the Chan Chen and Doubloon cores.

Few shells were recovered from the Buena Vista core. *Biomphalaria havanensis* (49% of total shells) was relatively more abundant here than in the other two marshes. Only one

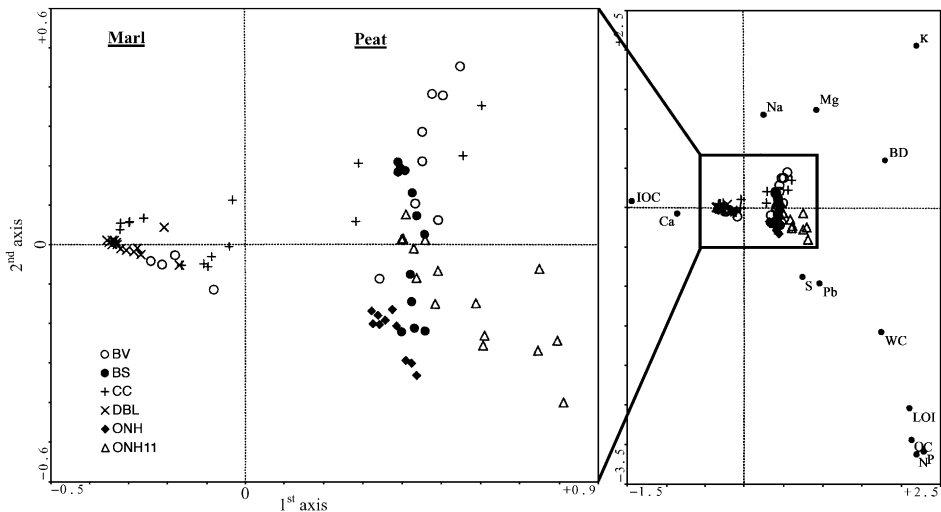


Fig. 13. Canonical correspondence analysis based on sediment characteristics, detrended by second-order polynomials, Hill's scaling and square-root transformation options. DBL: Doubloon, CC: Chan Chen, BV: Buena Vista, BS: Big Snail.

shell of *P. coronatus* (spinose), one of *Stenophysa spiculata* and one of an unidentified bivalve were found in the Big Snail core.

#### 4.6. Marsh characterization based on physical and chemical variables of sediment

Using 13 sediment properties, all 79 sediment samples were plotted in the space defined by DCA axes I and II (Fig. 13), which accounted for 74% and 12.8% of the total variance, respectively. The DCA diagram showed two distinct sediment groups, which correspond to the marl and peat (including clay). The cluster with negative values for the first axis was related to the high content of IC and Ca. This cluster included all the Doubloon samples, all the Chan Chen samples except the peat layer, and the 0–7-cm layer in the Buena Vista core. The marl containing live cyanobacteria is on the right side of this cluster because of slightly greater OC, N, P and K contents compared with the marl samples. The other large cluster with positive values for the first axis consists mainly of clay and peat. The positive part of the second axis is associated with clay and related components are Na, Mg, K and bulk density. The negative part is associated with peat. Related components are S, Pb, water content, OC, N and P.

The marl-based Doubloon sediments have the largest negative values for axis I and the sand-based ONH11 sediments generally have the largest positive values for axis I. Sediments from the other marshes form the remainder of these clusters. The distribution pattern of six marshes in Fig. 13 suggests a continuum from marl-based marsh to sand-based marsh in the following order: Doubloon, Chan Chen, Buena Vista, Big Snail, ONH and ONH11.

## 5. Discussion

### 5.1. Sediment chronology and accumulation rates

The  $^{210}\text{Pb}$  profiles in the marl-based marshes showed increase of  $^{210}\text{Pb}$  activity with depth in the upper marl layer containing live cyanobacteria (Fig. 2). Such increases in upper sediments in lake systems have been explained by changes in the sedimentation rate, mixing, slumping, or bioturbation (Robbins, 1978). An increase in  $^{210}\text{Pb}$  with depth to 10 cm is not common in lake sediments. Lake sediments generally include a thin layer of benthic algae, but the upper parts of the cores in these marl-based marshes consist of thick marl containing live cyanobacteria (epipelon). The productivity of the cyanobacteria is greater than the long term mean accumulation rate (Rejmánková and Komárková, 2000), and its rapid growth can dilute  $^{210}\text{Pb}$  activity in the live cyanobacterial layer. A progressively steepening decrease of  $^{210}\text{Pb}$  activities in ombrotrophic peat bogs has been explained by decomposition of organic matter (Appleby et al., 1997). We suggest that the low  $^{210}\text{Pb}$  activity in the uppermost part of the marl-based marshes results from the high growth rate of cyanobacteria and the rapid decomposition rate of dead cyanobacteria due to high temperature in the studied marshes. We have no experimental data on decomposition rates of benthic cyanobacterial mats, but the reviews of Leavitt (1993) and Sanger (1988) indicate that they decompose rapidly in warm conditions; over 90% of all chlorophyll can be destroyed within 15 days (Leavitt, 1993). Chlorophyll *a* decays

through cell lysis, viral attack, and other mechanisms (Leavitt, 1993), and the profile of chlorophyll *a* can be used to indicate decomposition of cyanobacteria. Chlorophyll *a* concentration in the marl-based marshes decreases to 0 at the depths with peak  $^{210}\text{Pb}$  activity (Figs. 2 and 3), which supports our suggestion:  $^{210}\text{Pb}$  that is initially highly diluted by cyanobacterial growth in marl-based marshes is concentrated by the rapid decomposition of dead cyanobacteria.

$^{210}\text{Pb}$  flux rates in the uppermost sediment were similar in all cores, ranging from 0.19 to  $0.28 \text{ pCi cm}^{-2} \text{ year}^{-1}$ , less than the global average of  $0.5 \text{ pCi cm}^{-2} \text{ year}^{-1}$  (Binford et al., 1993). Maximum  $^{210}\text{Pb}$  activities of 2.70–11.26 pCi/g in the three marl-based marsh cores were much less than these (10.36–20.27 pCi/g) in the three sand-based marsh cores. Even though  $^{210}\text{Pb}$  is concentrated by the rapid decomposition of dead cyanobacteria over a period of  $\sim 10$  years, the  $^{210}\text{Pb}$  activity of the peaks in the marl-based marshes must be around three-quarters of the original activity because of the decay of  $^{210}\text{Pb}$  (half life = 22.4 years) during this time. Maximum activity is, thus, less in marl-based marshes than in sand-based marshes even assuming the same sediment accumulation rate.

Lead (Pb) is widely cited as a marker of industrialization, particularly due to its use in automobile fuels from the 1920s until the early 1980s (Murray and Gottgens, 1997). We found a generally increasing concentration of total lead between the 1950s and 1960s in three of the marshes (Buena Vista, Big Snail and ONH11), but not in the others (Fig. 12). On average total lead content in the marl-based marshes was much greater than in the sand-based marshes. Profiles of total lead content suggest that a geochemical mechanism related to IC and Ca content binds lead in the sediment. Lead precipitates with carbonate at high pH to form  $\text{PbCO}_3$ , cerussite (Garcia-Delago et al., 1996a), and in this form it cannot move in the basic environments of the marl-based marshes (Garcia-Delago et al., 1996b). This mechanism accounts for the high total lead content in the marl containing live cyanobacteria and the marl layers in marl-based marshes. The lead content in Belizean marshes (20–50 ppm) is typically in the range of unpolluted soil. The world average is 29 ppm (Ure and Berrow, 1982) and values of 4.44–50.34 ppm were reported in Spain (Sanchez-Camacano et al., 1998) and of 18.1–131.7 ppm in wastewater irrigated soil in Mexico (Flores et al., 1997).

Dry mass accumulation rates in sand-based marshes were high in the late 1800s, especially the inorganic matter accumulation rate at ONH11, which corresponds with the onset of agricultural activities associated with forest clearance in the mid-1800s (Wright et al., 1959). The old main road from Belize City to Orange Walk passes beside the ONH11 marsh. Road construction and maintenance may have influenced marsh sediment characteristics. The population of northern Belize increased in the 1840s because of the arrival of farmers who cleared the forests. Agricultural and timber products were transported along this road. However, transportation problems and price fluctuations for agricultural products led farmers to abandon the farms. Many cocoa and sugar plantations were abandoned by 1895 (Wright et al., 1959). Heavy use of this unpaved road in the mid-1800s probably produced much dust, and heavy rain would have transported soil into the marsh, thus, increasing inorganic matter accumulation rate (Fig. 4). The marsh recovered from the severe input of inorganic matter in the early 1900s as road use decreased. There was then another increase in inorganic matter accumulation rate at ONH11 in the late 1950s, which corresponds with decreases in organic matter related elements at 4–8-cm depth (Fig. 10).

The unpaved road close to the marsh was improved at this time and this could have increased its use and the sediment accumulation rate. Overall sedimentation rates in our study sites are very similar to those obtained by Rejmánková et al. (1996) by  $^{137}\text{Cs}$  dating in the Buena Vista and Pulltrouser South marshes.

### 5.2. Average sediment accumulation rates

The sedimentation rate in our marshes was lower and total mass accumulation rate was higher than those reported for the Everglades (Table 4). Organic C, N and P accumulations were less than in northern unenriched areas of the Everglades for the past 25–30 years (Craft and Richardson, 1993). Later Craft and Richardson (1998) reported accumulation rates of C, N, P and S during the recent 100-year period based on  $^{210}\text{Pb}$  dating (Table 4). Sulfur accumulation was lower in sand-based marshes and higher in marl-based marshes in Belize than in the Everglades. Organic C, N and P accumulations in Belizean marshes were lower than in the unenriched phytogeographically similar region of the Everglades. Compared to other wetland types (Table 4), OC accumulation rate was higher than fens and lower than bogs and pocosins (peat-accumulating, nonriparian freshwater wetland, generally dominated by evergreen shrubs and trees) in the USA. Nitrogen accumulation rate was higher and P accumulation rate was lower than freshwater wetlands in the USA except for the Everglades. The above comparisons and the background sedimentation level indicate the relatively undisturbed condition of Belizean marshes except for the stable Pb and road effects.

### 5.3. Sediment characteristics

Nitrogen, OC and P contents was strongly associated with LOI in all the cores; correlation coefficients ( $r^2$ ) were 0.98, 0.99 and 0.52, respectively, suggesting P is mainly bound in refractory OM. Efficient recycling of P is a general trend in P-limited ecosystems (Belanger et al., 1989; Walbridge et al., 1991). Strong P deficiency in Belizean marshes has been confirmed by fertilization experiments for both cyanobacterial mats and macrophytes (Rejmánková and Komárková, 2000; E. Rejmánková unpublished data). This supports the suggestion that most P is bound to organic matter. IC was strongly correlated with Ca ( $r^2=0.99$ ), suggesting it occurs mainly in calcium carbonate. Pb is also correlated with IC ( $r^2=0.94$ ), suggesting it is bound largely as cerussite. The S content of the marl-based marsh sediments was much greater than in the sand-based marsh deposits because of the presence of gypsum (Rejmánková et al., 1996).

There were strong positive correlations among Ca, IC, Mg and S concentrations of samples from the marl layer. Contents of these elements in sediments were also positively correlated with surface water conductivity (Tables 1 and 3). The conductivity was related quantitatively to the Ca, Mg and Na concentrations of all sediments using stepwise multiple regression ( $R^2=0.928$ ,  $p<0.0001$ ):

$$\begin{aligned} \text{water conductivity } (\mu\text{S}) = & 0.012 \times \text{Ca (ppm)} + 0.322 \times \text{Mg (ppm)} + 0.237 \\ & \times \text{Na (ppm)} - 147.502 \end{aligned} \quad (2)$$

Table 4

Comparison of sediment accumulation rates (SR) and element accumulation rates of various wetlands in USA and Belize (OC = organic carbon)

Wetland type	SR (mm yr <sup>-1</sup> )	Mass (g m <sup>-2</sup> yr <sup>-1</sup> )	OC (g m <sup>-2</sup> yr <sup>-1</sup> )	N (g m <sup>-2</sup> yr <sup>-1</sup> )	P (g m <sup>-2</sup> yr <sup>-1</sup> )	S (g m <sup>-2</sup> yr <sup>-1</sup> )	Source
Belizean						0.3–1.0 <sup>a</sup>	
Marshes	0.9–1.6	162–603	29–56	2.4–4.5	0.04–0.12	1.7–5.0 <sup>b</sup>	This study
Everglades	1.6–4.0	144–360	54–96	3.8–7.6	0.06–0.14		Craft and Richardson (1993)
Everglades			97	6.5	0.06	18	Craft and Richardson (1998)
Fresh water wetland				1.2–3.8	0.06–0.90		Craft and Richardson (1998)
Fens			42				Kim and Rejmánková (2001)
Bogs			64–90				Kim and Rejmánková (2001)
Pocosins			127				Kim and Rejmánková (2001)

<sup>a</sup> In the sand-based marshes.

<sup>b</sup> In the marl-based marshes.

Rejmánková et al. (1996) reported that high water and soil conductivities, cation contents, salinities and soil Ca are associated with cyanobacterial mats and *E. cellulosa* in many wetlands in Belize as a result of salts other than NaCl.

#### 5.4. Historical water levels and salinity changes

Mollusc profiles and stratigraphy in the three marl-based marshes indicate historical changes in water level and/or salinity. A peat layer was found in all marsh cores, but only in the Doubloon and Chan Chen marshes was it under- and overlain by marl. Except in the Doubloon core, this peat layer had few or no molluscs (Fig. 12). Covich and Stuiver (1974) studied lake level change in Laguna Chichancanab using the  $^{18}\text{O}$  content of *Pyrgophorus* shells and concluded that high organic content, high density of *Pyrgophorus*, and high  $\delta^{18}\text{O}$  values indicated shallow water. The high density of molluscs in the peaty marl layer of Doubloon therefore suggest shallow water and increased food. The peat layer in Doubloon was more weakly developed than in Chan Chen; it was a peaty marl rather than pure peat. This implies that conditions for growth of peat-forming emergent macrophytes (most probably *C. jamaicense*) were less favorable in Doubloon probably because of deeper water or the greater salinity indicated by the higher water conductivity at Doubloon (Table 1).

Shells were not observed in the peat layer of Chan Chen core, and those adjacent to this layer were very fragile and largely decomposed. The upper marl mixed with live cyanobacteria in Chan Chen has fewer shells than the lower marl layer possibly because environmental conditions were not so favorable for *Pyrgophorus*. Peat-dominated marshes showed very low densities of *Pyrgophorus* spp.

Doubloon and Chan Chen are now relatively deep and flooded for most of the years, but they apparently experienced a shallow-water period between the late 1850s and early 1900s. The succession in the Buena Vista core did not show any marl below the peat layer, suggesting that this marsh was very shallow before 1850s.

As the Doubloon, Chan Chen, and Buena Vista marshes are spatially separated without any surface hydrologic connection, their synchronous change in water level was probably caused by the same environmental factor, such as climatic or sea level change. It has been argued that sea level controls water levels in marshes and lakes of the Yucatan Peninsula (Back and Hanshaw, 1970; Covich and Stuiver, 1974; Rejmánková et al., 1996) because most of the coastal plain aquifer consists of several metres of fresh water overlying saline water (Perry et al., 1989). However, sea level change may not have been the main control of water level in marshes during the last few hundred years because there has been a trend of rising sea level in the recent past (Gornitz, 1995) and our study showed a decrease of water level between the late 1850s and early 1900s. Oxygen isotope analyses of molluscs and ostracods from several lake cores in the Mayan area show a 100-year oscillation between wet and dry periods over most of the last 3500 years (Hodell et al., 1995; Curtis et al., 1996). The most recent oscillation indicates a major shift from wet conditions ca. 1800 AD to a peak drought in the mid-1870s, and then a return to wet conditions by the 1900s. Our results show that the water level in the study area decreased from the late 1850s until the early 1900s, coincident with the dry period reported by Hodell et al. (1995) and Curtis et al. (1996).

## 6. Conclusions

Our data showed higher accumulation rates of cations and IC in marl-based marshes than in sand-based marshes. Concentrations of cations and IC in sediment are related to water conductivity and this implies the main process of sediment formation is marl precipitation in marl-based marshes. The effect of human activities on increased sediment accumulation rate was observed only in sand-based marshes near roads, suggesting allochthonous inputs such as soil washout from adjacent roads.

The increase of  $^{210}\text{Pb}$  activity to a depth of 4–10 cm in the marl-based marshes was negatively correlated with the concentration of chlorophyll *a*, and we suggest that this reflects the high growth rate and high decomposition rate of the cyanobacterial mat. Stratigraphy and mollusc profiles indicated a decrease in water level between late 1850s and early 1900s and an increase since the early 1900s. The herbaceous peat layer was formed during the decreased period of water level in two of the marl-based marshes, presumably during the drought period documented by long-term  $\delta^{18}\text{O}$  records from lakes in the Yucatan region.

Statistical analyses of the physical and chemical characteristics of marsh sediment indicate that there are significant differences between marsh types. Doubloon represents an extreme type of marl-based marsh and ONH11 represents the most typical sand-based marsh. The distribution of marshes along this continuum is related to water conductivity.

Recent mean sedimentation rates during the last ~ 100 years were similar to long-term linear sedimentation rates in this region, and element accumulation rates were similar to those in unenriched areas of the Everglades. These results indicate the relatively undisturbed condition of Belizean marshes.

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