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HOLOCENE ENVIRONMENT CHANGES IN THE HACHICHINA WETLAND (GULF OF GABES, TUNISIA) EVIDENCED BY FORAMINIFERA AND OSTRACODA, GEOCHEMICAL PROXIES AND SEDIMENTOLOGICAL ANALYSES

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Abstract. Four sediment cores, drilled at Younga and Ouadrane Sebkhas (Hachichina wetland), were selected for micropalaeontological, sedimentological, geochronological and geochemical investigation coupled to hierarchical cluster and correspondence analysis. Our research aimed at reconstructing the past biodiversity, the Holocene palaeoenvironmental evolution and the responsible forcing. Subsurface sediments record four major phases: i) the first one is characterized by poorly to very poorly sorted silts, the dominance of the lagoonal/estuarine ostracod and the lagoonal/marine foraminifera and high values of terrestrial geochemical element ratios, such as K/Al and Fe/Al, which indicate an estuarine lagoon; ii) two major marine transgressions, TR1 and TR2, allowing the settlement of widely opened lagoons towards 7160-8680 and 5070-5520 cal yr BP, are marked by the enhancement of the marine/brackish ostracods and marine foraminifera, the improvement of species number, individuals number and H and E index values and of the marine element ratios such as Cl/Al and Sr/Al; iii) the opening of the lagoon is hampered by the action of drift currents allowing the genesis of sand spit and the settlement of a closed lagoon, towards 2610-3610 cal yr BP, characterized by the enhancement of lagoonal/estuarine ostracods and lagoonal/marine foraminifera and the increase of the individuals number; iv) the dominance of the lagoonal/estuarine ostracods and the lagoonal/marine foraminifera and the decline of the species number and density mark a brackish lagoon, also characterized by very poorly sorted silts transported by uniform suspension, which evolves to the actual sebkha. This evolution, within a global climate alteration context, from an estuarine environment to the present sebkha passing by an opened lagoon, is linked to the complex hydrographic setting of the sebkhas and of the Ouadrane Wadi outlet discharging in the Hachichina wetland.

INTRODUCTION

During the last decades, several proxies have allowed the reconstitution of Holocene climates and palaeoenvironmental evolutions and associated forcing. Globally, ocean surface reconstruction and estimates of sea surface temperatures are based on all predominant microfossil-based (transfer functions based on planktonic foraminifera, diatoms, dinoflagellate cysts, and radiolarians) and geochemical (alkenones and planktonic foraminifers Mg/Ca) thermometers. On the other hand, geoarchaeological and geomorphological surveys (Slim et al. 2004; Marriner et al. 2012; Salomon et al. 2018), corals (Siringan et al. 2016), speleothems (Genty et al. 2006) and marine and lake sediments are the important paleo-archives used for paleoenvironmental studies. The resolution of these paleoenvironmental records depends on the quality of these natural archives. Marine sediments offer some unique aspects for paleoenvironmental studies because of the continuity of the records. The resolutions provided are

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at the millennial to centennial time scale. In order to unravel the highly diverse and interactive properties recorded in marine sediments, geochemical methods (Giunta et al. 2001; Chagué-Goff et al. 2002; Martinez-Ruiz et al. 2015; Engel et al. 2016), sedimentologic approach (Benito et al. 2015; Donato et al. 2009), molluscs ecology (Donato et al. 2008), microfossil assemblages (Carbonel 1982; Mazzini et al. 1999; Zaibi et al. 2016; Frenzel & Boomer 2005) and multi-proxy study (Cuven et al. 2013; Wündsch et al. 2017; Khadraoui et al. 2018) have been used to develop proxies for paleoenvironmental studies.

Ostracoda and Foraminifera are increasingly applied to reconstitute Holocene palaeoclimate and environmental changes as seasonal conditions, hydrodynamic levels or physical-chemical restrictions at the water-sediment interface and tracing high resolution hydrological conditions (Ruiz et al. 2000a; Laprida 2001; Frenzel & Boomer 2005; Zaïbi et al. 2012, 2016). Their ecology and current distribution along the coastal fringe depend on marine and continental influences. Therefore, they are considered the most reliable biological proxies for the Holocene paleoenvironment reconstruction in relation with anthropological and natural forcing. On the other hand, ostracods living in paralic and endoreic environments are excellent hydrological tracers in the fresh-salt-water transition areas.

Regarding the Holocene series, the main climatic and eustatic sea level variations have been reconstructed based on quantitative and qualitative ostracod distributions (Carbonel 1982; Boomer & Godwin 1993; Mazzini et al. 1999; Sarr et al. 2009). The latter present reliable tools to recognize the different types of environments (Laprida & Bertels-Psotka 2003; Samir et al. 2003). Their eco-phenotypic variability and the stable isotopes and trace elements in their shells provide valuable information on present and past water salinity, temperature, chemistry, hydrodynamic conditions, substrate characteristics, climate, oxygen and nutrient availability (Carbonel 1982; Panieri 2003; Triantaphyllou et al. 2003; Frenzel & Boomer 2005). The most important parameters controlling the benthic foraminifera distribution are food availability, dissolved oxygen concentrations (De Rijk et al. 1999; Murray 2001), substrate type, temperature and salinity (Jorissen 1988; Samir et al. 2003; Hyams-Kaphzan et al. 2008; Phipps et al. 2010).

In Northern Tunisian coast, the analysis of ostracods and benthic foraminifera allowed the reconstruction of the freshwater, marine, lagoonal and estuarine Holocene palaeoenvironments. Carbonel & Pujos (1981) and Jouirou (1982) described the ostracods and foraminifera occurring in the surface and subsurface sediments of the lake of Tunis and lagoon of Bizerte and consisting of different assemblages of marine, open lagoon and closed lagoon environments (Fig. 1A). Ichkeul Lake, studied by Stevenson et al. (1993), and revised by our team (Ben Hamad et al. 2018) by means of descriptive paleontological proxies, records seven periods of brackish and fresh waters, during the last 3000 years. Ruiz et al. (2006) studied the El Melah Lagoon of Soliman and investigated its evolution to a future sebkha relying on the ostracod biozones. The Holocene evolution of Ghar El Melah Sebkha of Bizerte (Mansouri 1979), Korba Lagoon (Bouden et al. 2009) and Bou Zid Sebkha of Klibia (Farhat et al. 2010) seems to be controlled by the genesis of offshore bars. The Central Tunisian wetlands were studied by Ouda et al. (1998), Zaraï (2006), Amami (2010) and Henchiri (2014) who identified the different phases of humidity and aridity during the Holocene. The Gulf of Gabes coast is the most studied area via palaeontological proxies. In fact, Lachenal (1989) described Holocene assemblages of ostracods (phytal, opportunists and ubiquitous taxa) from the cores of the Gulf of Gabes and recognized the different regressive-transgressive phases. Zaïbi et al. (2011, 2012, 2016) examined the evolution of the South Skhira coast, by analyzing ostracods, foraminifera and molluscs and recognized the transgressive periods, the phases of sand spit genesis and the extreme events. Recently, Khadraoui et al. (2018) investigated the Northern coast of Sfax and identified two transgressive events, a wet period of build-up of sand spits, the genesis of a closed lagoon and a tsunami event.

In the present study, we used a multi-proxy approach in order to pursue the following research objectives: **i**) retracing the evolution towards the present sebkha system via distinct phases of connectivity to the open sea due to Holocene sea level and geomorphological changes (based on geochemical, foraminifera, ostracods and grain size data); **ii**) reconstructing changes in the terrigenous sediment supply as an indicator of the long-term wadi discharge and rainfall variability at the Hachichina

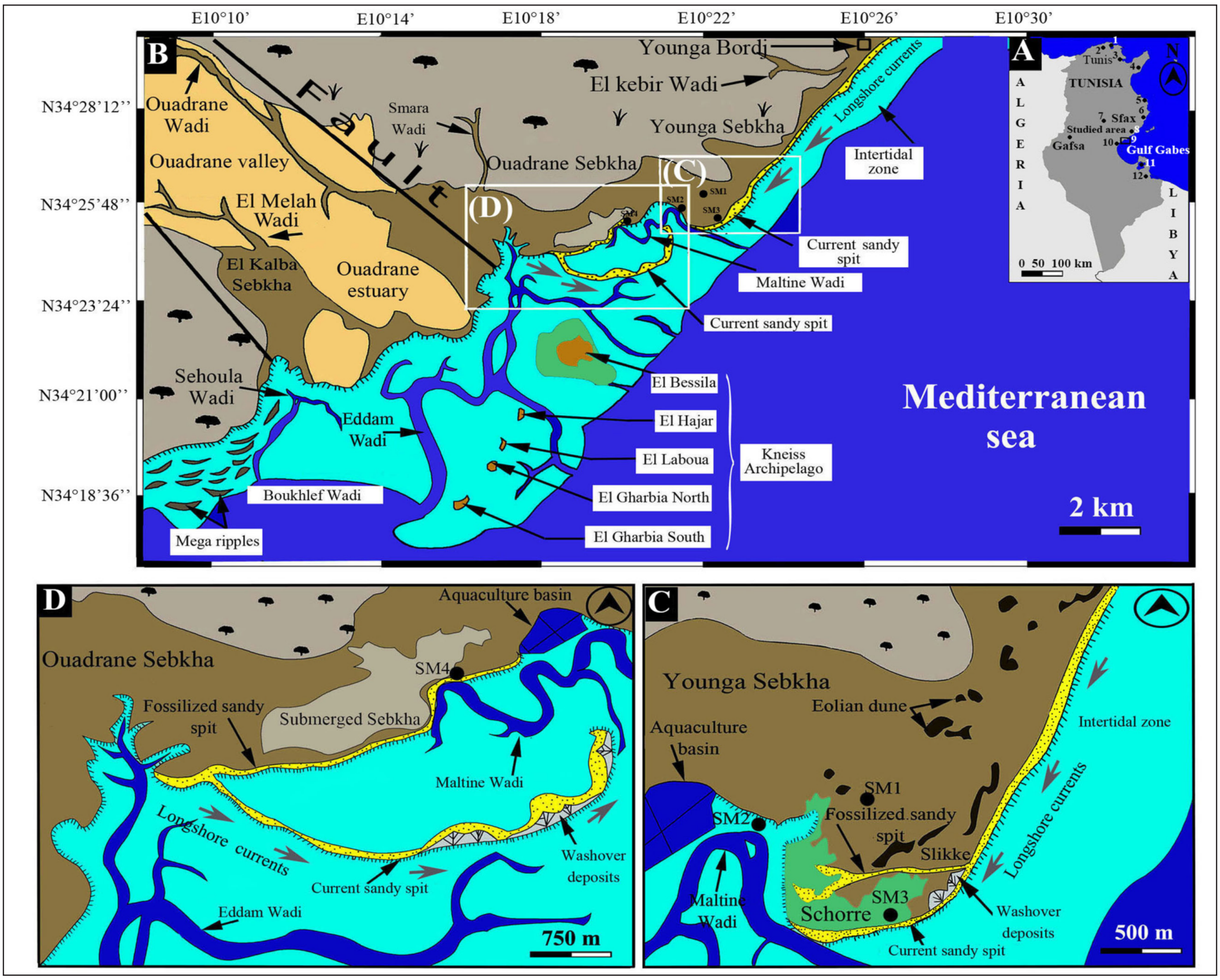


Fig. 1 - A) Location map of studied area and positions of localities cited in the text. 1: Bizerte Lake, 2: Ichkeul Lake, 3: Tunis Lake, 4: Korba Lagoon, 5: Rass Dimass lagoon, 6: Ras Botria lagoon, 7: Maknassy area, 8: Gargour coast, 9: Hachichina wetland (studied area), 10: Dreiia Sebkha, 11: Bin El Oudiane Lagoon, 12: Boujmel Sebkha. B) Hachichina coast: Location of Ouadrane and Younga Sebkhas, distribution of different littoral environments, geomorphological units, position of Kneiss Archipelago and associated tidal channels (Google Earth, mission 2019). C) Detailed view of Younga Sebkha, distribution of different littoral environments, geomorphological units and positions of cores. D) Detailed view of Ouadrane Sebkha, distribution of different littoral environments, geomorphological units and positions of cores.

wetland embayment during the last 7.5 kyr (using geochemical and grain size data), and **iii**) comparing this evolution to that of Tunisian and Mediterranean coasts.

GEOMORPHOLOGY AND GEOLOGICAL SETTING

The Hachichina coast (Fig. 1B), characterized by a regular topography and a complex coastline, is located in the central part of Gabes Gulf at 3 Km to the South of Mahras City. The Hachichina wetland has a warm and arid climate, with annual rainfall of only about 150 mm, and semi-diurnal tides ranging from 80 to 130 cm. This wetland shows the presence, from the North to the South, of three sebkhas named Younga, Ouadrane and El Kalba and associated lagoons and different zones with geomorphological characteristics, arranged from West to East as follows:

i) land characterized by the presence of several archaeological sites and developed vegetation with a succession, from East to West, of *Salicornia* and olive plantations. The morphostructural map of this area reveals the presence of a corridor of N120-140 faults (Bedir 1995; Ghribi 2010) which control the deviation of an intermittent streams course, locally called Ouadrane and El Melah Wadis, oriented in E-W upstream and NW-SE downstream. Ouadrane and El Melah Wadis feed the Hachichina wetland overland flow and allow the individualization of an important valley and estuary;

ii) a supratidal zone, corresponding to the sebkhas and extending over 2 Km landward. The surface sediments of the sebkhas are constituted by a centimetric level of gypsum overlying silty sands/clays rich with salt crystals. Younga Sebkha (Figs 1B and 1C), with an area of about 4 Km^2 is limited in the North by the archaeological site Younga Bordj, characterized by the presence of several Roman ruins and El Kebir Wadi. It is enclosed by aeolian dunes of up to 1.5 m in height and constituted by a gypsiferous material. A system of sand spit, 2 Km long, resulting from Southern longshore currents, separates the sebkha from the open sea and preserves a small lagoon subjected to marine influences by means of a tidal channel (Maltine Wadi). Ouadrane Sebkha, more extended than the previous one and covering 8 Km^2, is limited in the South by Ouadrane Wadi and its associated estuary (Figs 1B and 1C). It is separated from the sea by a sand spit of 8 Km in length, which also creates a large isolated lagoon. The opening towards the sea is assured by a main tidal channel (Maltine Wadi), which penetrates in the lagoon and delimits the schorres and the slikkes, by-passing the sand spit and by Eddam Wadi which penetrates the submerged sebkha.

Several fossilized prograding sand spits can be observed in the associated lagoons of the two sebkhas via satellite images (mission 2019). The latter also show the impact of storms on the coast morphology, washover deposits (Figs 1C and 1D), and in the tidal zone at the southern mouth of Ouadrane estuary, a system of mega-ripples mainly oriented East-West, and other directions associated with refracted waves are also distinguished (Fig. 1B). The two sebkhas are episodically inundated by seawater during the exceptional tides and storms;

iii) an intertidal zone made up of silty sands. It extends about 800 m in front of the sebkhas and reaches 6 Km to the South in front of Ouadrane estuary. Several Roman ruins, submitted to the wave action, can be observed along the Hachichina coastline. The intertidal substratum is characterized by its richness in suspensivorous and herbivorous bivalves (*Ruditapes decussatus, Fulvia fragilis, Callista chione* and *Venus verrucosa*) and gastropods (*Cerithium vulgatum*, *Hydrobia ventrosa* and *Bittium reticulatum*);

iv) a subtidal zone characterized by shallow water. The isobath of 20 m is 10 Km away from the coastline. The subtidal substratum is rich with Phanerogams, mainly *Posidonia oceanica* and *Cymodocea nodosa*;

v) in front of the Ouadrane estuary, we meet five islands named El Gharbia South, El Gharbia North, El Laboua, El Hajar and El Bessila, of different shapes and sizes (Fig. 1B). These islands, constituting Kneiss Archipelago, are oriented NE-SW and parallel to the coast. The substratum of the intertidal zone around these islands is constituted by vast mud and sand flats covered by eelgrass beds *Zostera* (*Zosterella*) *noltei* and extending over 100 Km^2. It is crossed by several tidal channels such as Eddam, El Maltine, Boukhlef and Sehoula. These channels, controlled by several faults, delimit the islands. They are indeed an extension of the Ouadrane and El Melah Wadis of the hinterland. Kneiss Archipelago extent, whose substratum is constituted by tyrrhenian sands, has greatly diminished since the Middle Age, which was favored by low altitudes probably due to the rise in relative sea level. In addition, the marine erosion reduced the size of the islands and generated the resulting cliff retreat.

MATERIAL AND METHODS

Field coring and sampling

Core sediments have been obtained from four boreholes (SM1 to SM4) drilled in the emerged area of the Younga and Ouadrane Sebkhas. The locations of cores, positioned using differential GPS (Magellan Pro-Mark X), are situated at 34°25'58.64"N-10°22'0.90"E (SM1), 34°25'31.48"N-10°21'23.67"E (SM2), 34°25'9.94"N-10°22'4.36"E (SM3) and 34°25'14.18"N-10°19'52.46"E (SM4). The cores were preserved until their arrival in the laboratory and then divided longitudinally in two halves. One-half was archived and the other one was described visually (sediment types, structure, color and organic constituents), photographed and sampled at 5 cm for microfauna analysis and at 10 cm intervals for grain size and geochemical studies.

Analytical techniques

Granulometric preparation and computation of the grains parameters. A total of 64 samples, taken from the sediment cores SM1 (33 samples), SM3 (18 samples) and SM4 (13 samples), were washed over 63 and 125 µm meshes and the different fractions (< 63 µm, 63-125 µm and > 125 µm) were determined. Grain size measures were carried out on 2 grams of the dry sediment, which underwent wet sieving using a sieve of 1000 µm to separate the coarser fraction from the fine one (<1000 µm). The fine fraction was then analyzed using a Malvern Mastersizer 3000 Laser Particle Analyzer. The grain-size distribution of samples was then averaged. Mean grain-size (Mz), sorting or standard deviation (SD) and skewness (Sk) were calculated geometrically (in µm) and logarithmically (using the φ scale) according to Folk & Ward (1957). The grain-size parameters described in the following sections are commonly used to characterize sedimentary environments and evaluate transport processes and deposition mechanisms and differentiate various modes of fluvial and marine transports (Passega 1957, 1964; Ramanathan et al. 2009; Rajganapathi et al. 2013; Warrier et al. 2016).

Micropalaeontological preparation, taxonomical identification and calculation of biocenotic parameters and diversity indices. The collected samples were dried at 40°C and their dry weight was determined. Next, they were washed over 63 and 125 µm meshes. From each sample, specimens were picked from the 125 µm fraction and observed under a binocular microscope at 20 to 40 times magnification and foraminifera and ostracods were identified. All specimens of microfauna, contained in one aliquot, were hand-picked using a wet brush. If less than 300 specimens were present per aliquot, the second aliquot was picked. This number guarantees a representative population for the high diversity assemblages. The average weight of the samples being 5 grams, the values obtained were reported to 1 gram of dry sediment. We consider only the taxa with a minimum of occurrence of 5% for ostracods and 10% for foraminifera taxa for the differents cores. Also, the allochtonous ostracods are recognized on the base of population structure revealed by the ratio between juvenile and adult individuals (Laprida 2001). The taxonomical ostracod identification keys were provided by Bonaduce et al. (1975), Llano (1981), Carbonel (1982), Athersuch et al. (1989) and Zaïbi et al. (2016) and by Jorissen (1988) and Cimerman & Langer (1991) for foraminifera (Tab. 1). The identified assemblages (ostracods and benthic foraminifera) were compared to those of the Tunisian and Mediterranean coasts. The software package PAST V 2.04 (Hammer & Harper 2001; Hammer et al. 2008) was used for numerical analyses of the absolute abundance or density (number of individuals/gram of sediment), specifies richness (NS), Shannon Index (H) (Shannon & Weaver 1949), Equitability index (E) (Pielou 1966) and Dominance (D).

Preparation of samples for geochemical analysis. Each sample was crushed until reaching a very fine fraction of the order of a few micrometers. The obtained powder was packed in a capsule and covered by a plastic membrane. Geochemical analysis was performed on powder by means of a Niton FXL, X-ray fluorescence (XRF) analyzer by Thermo Scientific to identify the concentration of seven elements. Geochemical characteristics such as the concentration values of the marine elements Ca, Cl and Sr (Judd et al. 2017) and the terrigenous elements Fe, Al, SiO_2 and K (Chagué- Goff et al. 2002), normalized to Al element (Martinez-Ruiz et al. 2015), can be correlated with the sediment source. Engel et al. (2016) noted that the peaks in dissolved salts (Ca, Cl, S) may indicate marine flooding but provide no evidence for the depositional process; however, increases in terrestrial ions (Fe, K) may be used to trace the continental influence.

Radiocarbon preparations and calibration. Five radiocarbon datings on Mollusc shells were considered to determine control ages for lithological units. The ^{14}C datings were carried out at the Mesure du C14 (ARTEMIS) Saclay (France) and at the Isotopic and Palaeoclimatology (National School of Engineers, Sfax, Tunisia) laboratories. All samples were prepared following a standard procedure (Délibrias 1985): shells were mechanically cleaned by adding contaminants and leached with dilute HCl to remove portions of shell matrix that might have been affected by exchange reactions and recrystallisations (Vita-Finzi & Roberts 1984). Depending on the $\delta^{13}C$ values, each sample was calibrated using MARINE13 calibration curves (Reimer et al. 2013) and the CALIB radiocarbon calibration software (version 7.1.0); (Stuiver & Reimer 1993), with a marine reservoir effect of 390±85 yrs and $\Delta R=35\pm70$ yrs (Siani et al. 2000) for the modern period and Siani et al. (2001) for the last 6000 yr in the Mediterranean Sea. The ages discussed below

Tab. 1 - List of benthic foraminifera and ostracods species identified in this work.

FORAMINIFERA	OSTRACODS
Adelosina longirostra (d'Orbigny, 1826)	*Aurila convexa* (Baird, 1850)
Ammonia beccarii (Linné, 1758)	*Aurila prasina* (Barbeito-Gonzalez, 1971)
Ammonia parkinsoniana (d'Orbigny, 1839)	*Aurila* sp.
Ammonia sp.	*Aurila woodwardii* (Brady, 1868)
Ammonia tepida (Cushman, 1926)	*Basselerites berchoni* (Brady, 1869)
Cribroelphidium incertum (Williamson, 1858)	*Carinocythereis carinata* (Roemer, 1838)
Elphidium aculeatum (d'Orbigny, 1846)	*Cushmanidea elongata* (Brady, 1868)
Elphidium advenum (Cushman, 1922)	*Cyprideis torosa* (Jones, 1850)
Elphidium crispum (Linnaeus, 1758)	*Cytheretta adriatica* (Ruggieri, 1952)
Elphidium macellum (Silvestry, 1900)	*Cytheromorpha fuscata* (Brady, 1869)
Elphidium simplex (Cushman, 1933)	*Hiltermannicythere emaciata* (Brady, 1867)
Haynesina sp.	*Leptocythere fabaeformis* (Mueller, 1894)
Masselina secans (d'Orbigny, 1839)	*Leptocythere pellucida* (Baird, 1850)
Quinqueloculina agglutinans (d'Orbigny, 1839)	*Leptocythere* sp.
Quinqueloculina annectens (d'Orbigny, 1839)	*Loxoconcha elliptica* (Brady, 1868)
Quinqueloculina laevigata (d'Orbigny, 1839)	*Loxoconcha rhomboidea* (Fischer, 1855)
Quinqueloculina lamarckiana (d'Orbigny, 1839)	*Neocytherideis faveolata* (Brady, 1868)
Quinqueloculina limbata (d’Orbigny, 1826)	*Semicytherura incongruens* (Mueller, 1894)
Quinqueloculina padana (Perconig, 1954)	*Semicytherura sella* (Sars, 1866)
Quinqueloculina parvula (Schlumberger, 1894)	*Semicytherura videns* (Mueller, 1894)
Quinqueloculina seminula (Linnaeus, 1758)	*Urocythereis oblonga* (Brady, 1866)
Rosalina bradyi (Cushman, 1915)	*Xestoleberis aurantia* (Baird, 1838)
Rosalina macropora (Hofker, 1951)	*Xestoleberis dispar* (Mueller, 1894)
Rosalina sp.	
Siphonaperta agglutinans (d'Orbigny, 1839)	
Siphonaperta aspera (d’Orbigny, 1826)	
Siphonaperta irregularis (d’Orbigny, 1878)	
Spiroloculina tenuiseptata (Brady, 1884)	
Triloculina tricarinata (d'Orbigny, 1839)	

are expressed as the total interval age of the 2 σ calibrated range.

Multivariate data analysis

The abundance of ostracods and foraminifera species was treated in an R-mode cluster analysis, performed using paired group algorithm and the Bray-Curtis similarity on the raw data of major species > 5% for ostracods and > 10% for foraminifera. We used the results of the cluster analysis to identify assemblages, provide ecological remarks and adopt the results to perform the paleoecological interpretation. To verify the results of the descriptive study and diversity indices, a Correspondence Analysis (CA) was realized based on ostracods and foraminifera absolute abundance and species number and density values (as a supplementary variables) by means of Past Software. The core SM1 was herein selected for the multivariate data analysis because it outperformed the other sample cores in thickness (about 3 meters) and richness in microfauna and dated levels.

RESULTS

Sedimentology and macrofauna

Core SM 1. The core SM1, 330 cm long, consists of seven lithological units (Fig. 2) showing different mean grain sizes, standard deviations (Fig.

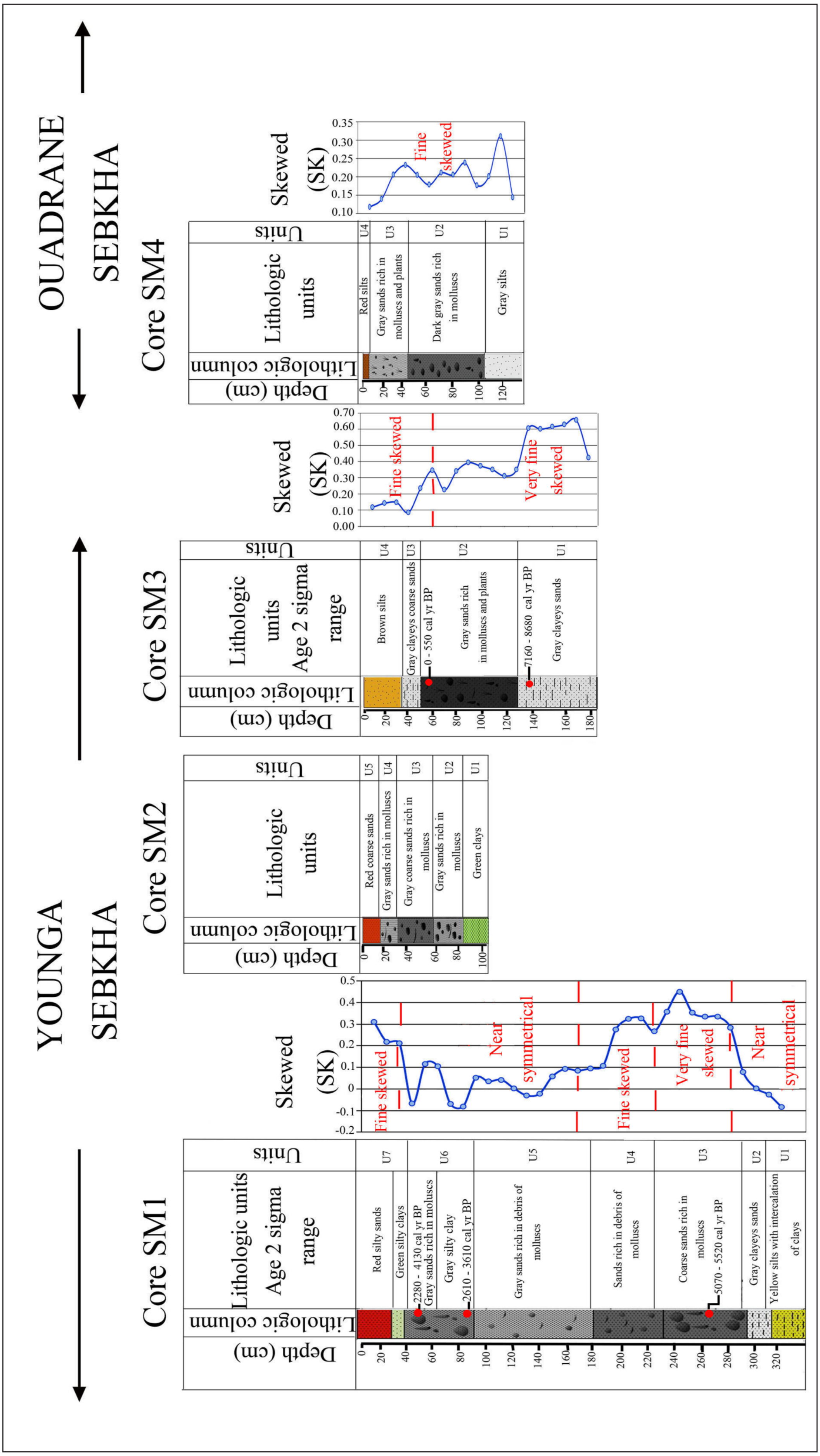


Fig. 2 - Distribution of Skewed (SK) size parameters, lithological units, calendar age and sediment texture (< 63 µm represented in black, between 63 µm and 125 µm represented in dark gray and > 125 µm represented in light gray) of SM1, SM2, SM3 and SM4 cores.

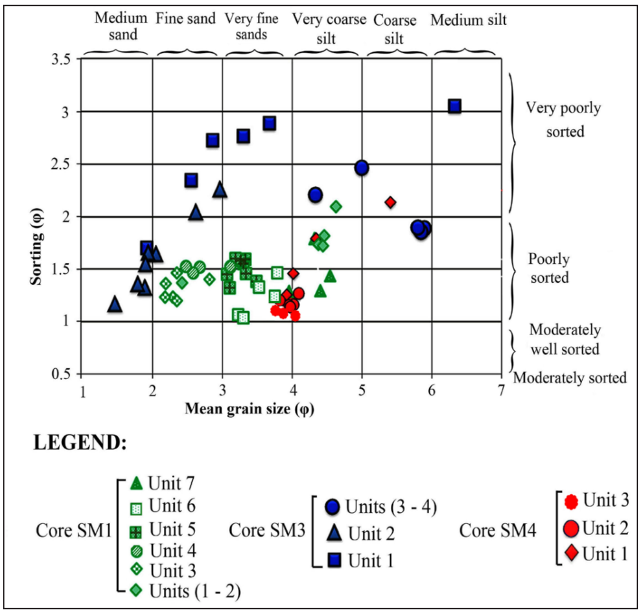


Fig. 3 - Relation between mean grain size and standard deviation of the subsurface sediments of the selected SM1, SM3 and SM4 cores.

3) and transport process (Fig. 4). The lowest unit (U1), 330-305 cm, is made up by yellow silts with clay intercalations. It shows a mean grain size varying between 4.3 and 4.5 φ and a standard deviation between 1.7 and 1.8 φ indicating a poorly sorted sediment. The values of the first percentile range from 320 to 450 µm and of the median percentile vary from 28 to 45 µm. They indicate a transport by uniform suspension process. The second unit (U2) from 305 to 290 cm corresponds to poorly sorted gray clayey silts (1.7<So<2) showing the high energy of the environment, comparable with the previous unit. The transport by uniform suspension is proved by the Passega diagram. The grains of both units (U1 and U2) displayed near symmetrical distribution (-0.1<Sk<0.1). The interval from 290 to 180 cm (U3 and U4) is made up of sands organized in a fining upward sequence. U3, from 290 to 230 cm, reveals the presence of bivalves and gastropoda associated with lithoclasts in coarse sands. It shows a mean grain size varying between 2.3 and 2.8 φ and a standard deviation between 1.1 and 1.5 φ indicating a poorly sorted sediment. Grain size presents a very fine skewed distribution. The Passega diagram levels of U3 show a mode of transport by suspension and rolling. In U4, from 230 to 180 cm, the grains present a fine skewed distribution, their mean size varies from 2.6 to 3.1 φ and they are characterized by the presence of fine debris of molluscs in sands. Representative points of this interval show that the mode of sediment transport corresponds to suspension and rolling, as the previous unit, represented by QP segment. The unit U5, from 180 to 95 cm, is characterized by gray sands with mean grain size ranging from 3.2 to 3.8 φ and containing fine mollusk debris. SD is between 1.3-1.5, showing poorly sorted sediment. Grain size presents a near symmetrical distribution (0 <Sk<0.1) and the plots of CM patterns show that the sediments are transported by graded suspension no rolling process.

U6, from 95 to 40 cm, corresponds to gray silty clays overlaid by gray sands rich in lagoonal molluscs such as *Cerastoderma glaucum* and *Abra alba* and lithoclasts. Mean grain size varies between 3.2 and 3.7 φ and the standard deviation ranges from 1 to 1.4 φ, signifying a poorly-sorted sediment. Grain size presents near symmetrical distribution. The levels of the silty clays (interval between 95 and 60 cm) reveal a process of grain transport by uniform suspension, while the upper levels, constituted by sands (from 60 to 40 cm), show a transport by graded suspension no rolling (Fig. 4). The unit U7 corresponds to green silty clays overlaid by red silty sands with salt crystals. The grain size varies between 3.8 and 4.5 φ and displays a fine skewed distribution. The silts of this zone are transported by a uniform suspension process.

Core SM2. The core SM2, 104 cm long (Fig. 2), contains five lithological units. The lower unit U1, from 104 to 80 cm, is characterized by green clays. The second unit U2, 80-60 cm, is made up of gray sands rich in lagoonal bivalves such as *Cerastoderma glaucum* and *Abra alba* and gastropoda represented by *Cerithium vulgatum*. From 60 to 25 cm, U3 is formed by coarse sands rich in bivalves and gastropoda. The unit U4, 25-15 cm, is characterized by gray sands rich in molluscs.

The last 15 cm (U5) are constituted by red coarse sands.

Core SM3. Four lithological units named U1 to U4 are identified (Fig. 2). U1, from 185 to 135 cm, with a mean grain size varying between 2.5 and 3.8 φ, showing fine to very fine sands and very poorly sorted grains (Fig. 3), presents a very fine skewed distribution. The grains are transported by a suspension and rolling process. Unit U2, from 135 to 45 cm, is made up by poorly sorted gray sands rich in phanerogams. The mean grain size varies

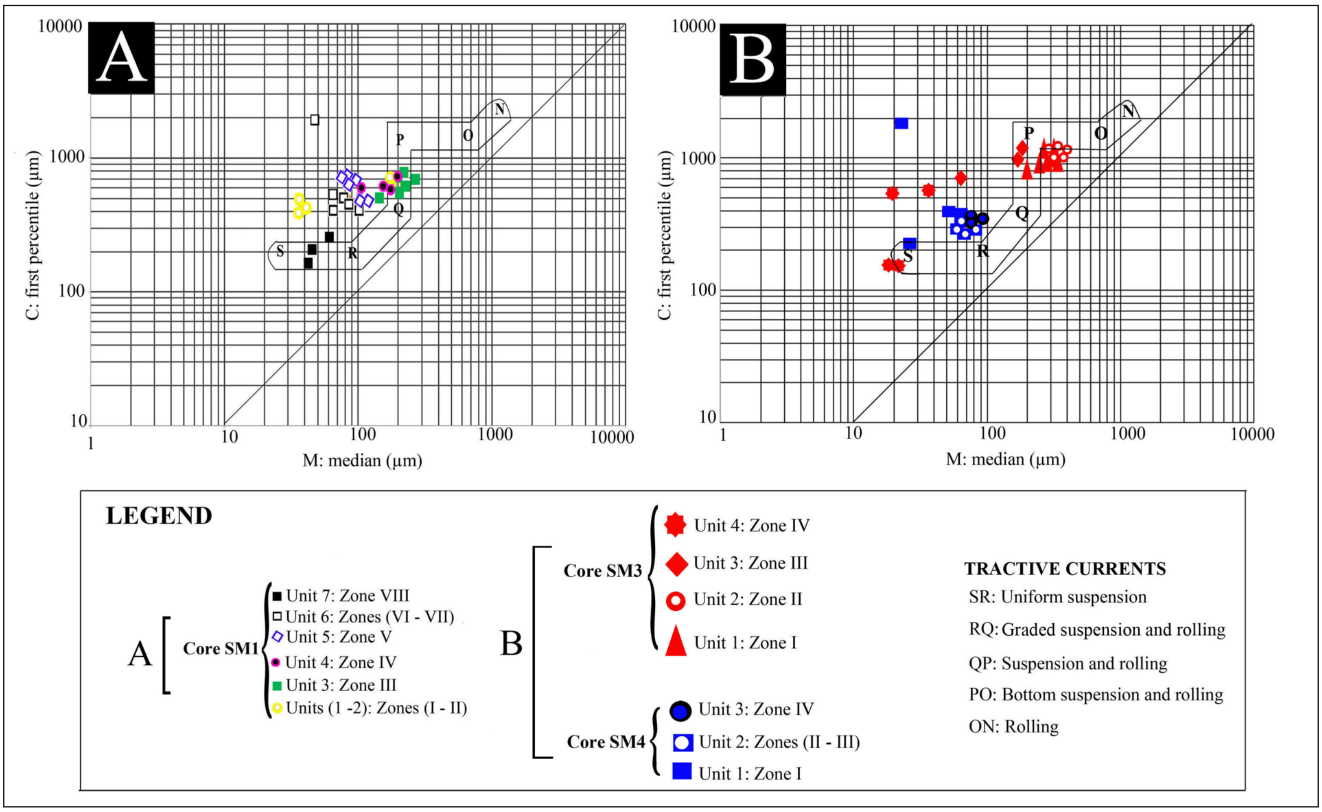


Fig. 4 - Passega diagram of SM1, SM2 and SM3 cores sediments.

between 1.4 and 2.9 φ. Intact brackish bivalves and gastropoda coupled to a rich lithoclasts and debris of molluscs appear in the upper part of U2 and indicate high energy deposit. Grain size parameters and the plots of CM patterns show a bottom suspension and rolling transport (Fig. 4). U3, from 45 to 30 cm, corresponds to a poorly to very poorly sorted gray clayey coarse sands where the mean grain size varies between 4.3 and 5.7 φ. The grains are transported by suspension and rolling. Unit U4, from 30 cm to the surface, is composed by poorly sorted brown silts transported buy uniform suspension**.**

Core SM4. It reveals the following lithological units (Fig. 2). U1, from 130 to 105 cm, is characterized by a gray silt with mean grain size varying between 4.1 and 4.8 φ. Standard deviation is from 1.2 to 2.2. The measure of the dispersion of grain size according to a central value indicates poorly sorted very coarse silts (Fig. 3). Grain size presents a fine skewed distribution. The plotting of CM diagram of the unit U1 levels shows a transport by uniform suspension (Fig. 4). U2, from 105 to 45 cm, is characterized by dark gray sands rich in molluscs, with mean grain size ranging from 3.9 to 4.2 φ. Standard deviation is between 1.3 and 1.4 φ, revealing a poorly-sorted coarse silts. U3, from 35 cm to the surface, is made up of gray sands overlaid by red silts. The mean grain size varies from 3.8 to 4 φ. U3 is rich in bivalves and vegetable debris. Standard deviation values, varying from 1.2 and 1.4, indicate a poorly sorted sediment. Grain size presents a fine skewed distribution and the plotting of CM diagram shows a transport by graded suspension and no rolling (Fig. 4).

Dating

Three radiocarbon ^{14}C datings on bivalves and gastropoda were determined for the core SM1. In addition, two ^{14}C datings were obtained for the core SM3 (Tab. 2). The top horizon (45-48 cm) of the core SM1 is a little older than the middle horizon (80-85 cm). This suggests that the upper ten centimeters of the unit U6, characterized by uniform coarse-grained sediments, were deposited after a high-energy event. This event ultimately lead to a reworking of sediments and may explain the slight reversal of radiocarbon dates within the top layers of SM1. Our age model is herein built on ^{14}C datings obtained from gastropod and bivalve shells. However, nearshore coastal sediments are subject to intense processes of sediment dynamics and require a careful interpretation of dated sediments.

Cores	Depth (cm)	Studied material	Age ^{14}C a BP	Range 1 sigma (68.3%) cal a BP	Range 2 sigma (95.4%) cal a BP	Median age a cal BP	Laboratory
SM1	45 – 48	*Gastropoda and Bivalvia*	3356 ±362	2720 – 3620	2280 – 4130	3170	Isotopic and Palaeoclimatology E.N.I.S. (Sfax, Tunisia)
SM1	80 – 85	*Gastropoda and Bivalvia*	3297 ±195	2840 - 3330	2610 –3610	3090	Isotopic and Palaeoclimatology E.N.I.S. (Sfax, Tunisia)
SM1	261 – 264	*Cerithium vulgatum*	5015 ±30	5250 – 5440	5070 – 5520	5330	Mesure du C14 (ARTEMIS) Saclay France
SM3	50 –60	*Gastropoda and Bivalvia*	658 ±192	80 – 425	0 – 550	270	Isotopic and Palaeoclimatology E.N.I.S. (Sfax, Tunisia)
SM3	140 – 150	*Gastropoda and Bivalvia*	7445 ±359	7545 – 8260	7160 -8680	7890	Isotopic and Palaeoclimatology E.N.I.S. (Sfax, Tunisia)

Tab. 2 - ^{14}C ages obtained for the lithologic units of SM1 and SM3 cores. Age ^{14}C in yr BP, calibrated ages with 1 sigma range and with 2-sigma range and median age in yr BP.

Micropalaeontology

Autoecology of ostracods and benthic foraminifera. Cluster analyses on ostracod and foraminifer taxa were herein used for paleoecological purposes. For each population, only sixteen taxa presented a relative abundance >5% for ostracods and 10% for foraminifera in at least one sample were considered. Cluster analysis in R-mode allowed us to distinguish 16 major species, putting in evidence 3 clusters of taxa (Cl.1 to Cl.3) for ostracods and 2 clusters (Cl.1-Cl2) and 3 single ones for foraminifera, when a cut-off level of 0.18 for ostracods and of 0.40 for foraminifera are applied to the clusters. These clusters are regarded herein as biotopes and interpreted as representing ecological conditions (Tab. 3 & Figs I to IV in supplementary material).

Ostracods. The first cluster (Cl.1) corresponds to the coastal/marine assemblage (Fig. 5a), which encompasses the polyhaline-euhaline *Neocytherideis faveolata*, *Semicytherura sella* and *Leptocythere* sp. with a maximal abundance of 13%, 7.5% and 18% between 320 and 280 cm, respectively (Figs 5b and 5c). Cluster 2 (Cl.2), consistent to a lagoonal/estuarine assemblage, includes the typically oligo-mesohaline to very euryhaline *Cyprideis torosa* and *Xestoleberis aurantia.* It is observed from 280 to 160 cm and essentially from 100 to 35 cm, with height contribution (90%). From 280 cm to 160 cm in depth, *C. torosa* is almost totally absent while *X. aurantia* is dominant, reaching 80% (Figs 5b and 5c). However, from 100 cm to 35 cm *C. torosa* replace progressively *X. aurantia* until its complete disappearance. This evolution is characteristic of a closed lagoon evolving to a brackish one under fresh water influence. Cluster 3 (Cl.3), richer in ostracods than the previous, can be subdivided into two sub-clusters (Fig. 5a). Between 320 and 280 cm, Cl.3a, corresponding to a coastal/estuarine assemblage, contains the polyhaline-euhaline *Aurila convexa* (5%) and *Aurila* sp. and the oligo-mesohaline *Cytheromorpha fuscata* (20%) (Fig. 5c). In this interval, we also noted the maximal contribution of polyhaline-euhaline specie from Cl.1. The mixture between species characterized by different ecologic affinities marks a lagoonal environment submitted to freshwater influences. The richer Cl.3b, corresponding to marine/brackish assemblage, gives a maximal contribution from 160 to 100 cm. It can also be subdivided into two sub-clusters Cl.3b1 and Cl.3b2 (Figs 5a and 5c). The first one, Cl.3b1, contains the polyhaline-euhaline, *Loxoconcha rhomboidea, Semicytherura incongruens, Carinocythereis carinata*, *Hiltermanicythere emaciata, Cushmanidea elongata* and the very euryhaline *Loxoconcha elliptica.* Cl.3b2 contains the polyhaline-euhaline *Leptocythere fabaeformis* and *Leptocythere pellucida.* The dominance of the polyhaline-euhaline taxa of cluster 3 indicates a lagoonal environment.

From 280 to 160 cm, the contribution of Cl.3 seems comparable to that of Cl.2. This interval is marked by the presence of the dominant polyhaline-euhaline taxa of Cl.3b1 associated to those of Cl.2 including *Xestoleberis aurantia* and by the complete disappearance of the euryhaline *C. torosa* and the reduction of *L. elliptica.* This interval signs a lagoonal environment opened to the sea with restricted fresh water influences.

Foraminifera. The first cluster (Cl.1) corresponding to a marine assemblage can be subdivid-

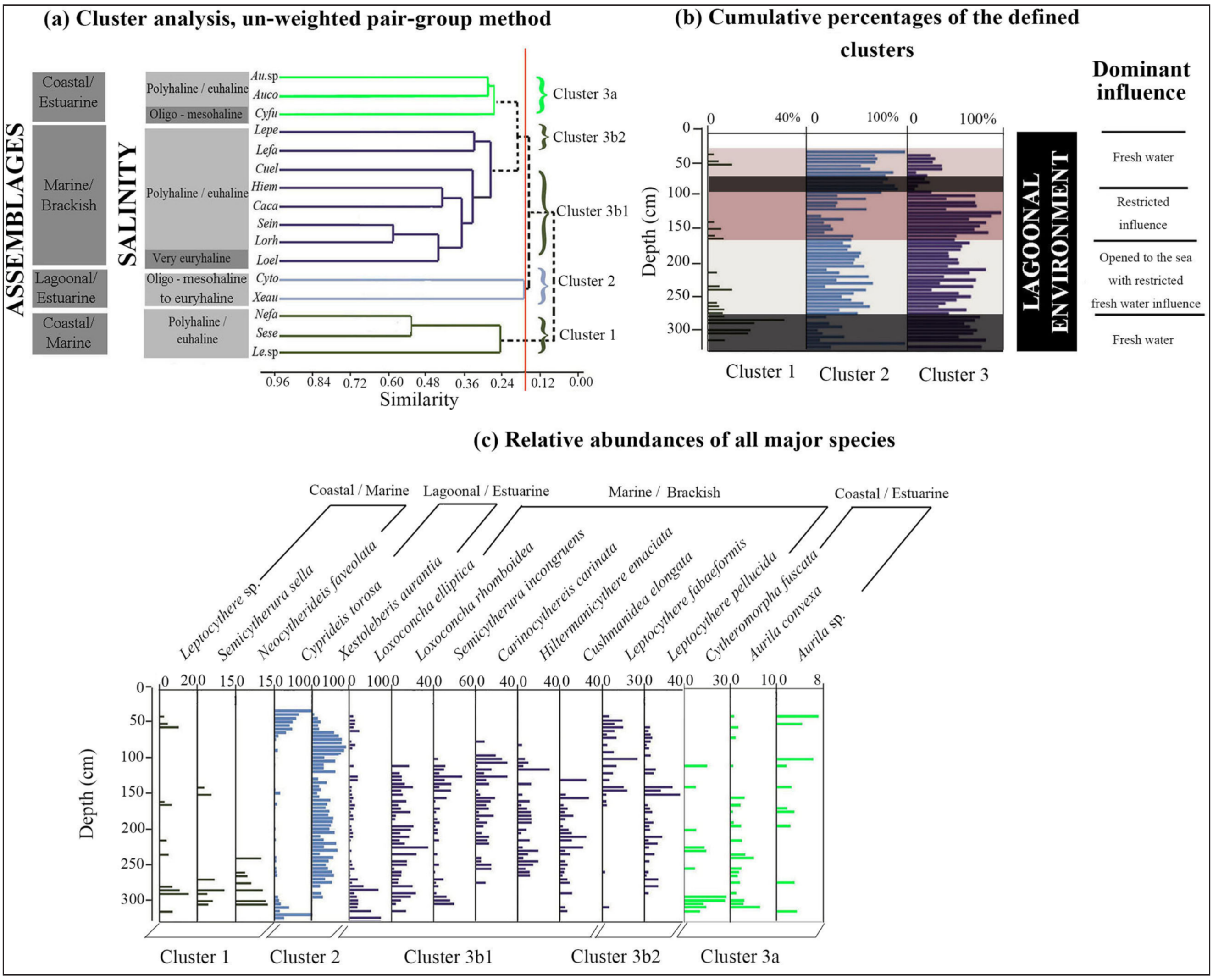


Fig. 5 - a) R-mode cluster analysis performed on the 16 fossilized major ostracod species (> 5% in at least one) of the 65 investigated samples showing the clusters Cl.1, Cl.2 and Cl.3 and the sub-clusters (Cl.3a, Cl.3b1 and Cl.3b2). b) Cumulative percentages of taxa composing the defined clusters along core SM1. c) Relative abundance of all major species along the core SM1.
Ostracods taxa abbreviations: *Xestoleberis aurantia* (*Xeau*), *Loxoconcha rhomboidea* (*Lorh*), *L. elliptica* (*Loel*), *Cyprideis torosa* (*Cyto*), *Hiltermannicythere emaciata* (*Hiem*), *Carinocythereis carinata* (*Caca*), *Aurila convexa* (*Auco*), *Aurila* sp. (*Asp*), *Leptocythere fabaeformis* (*Lefa*), *L. pellucida* (*Lepe*), *Leptocythere* sp. (*Le.* sp), *Cytheromorpha fuscata* (*Cyfu*), *Semicytherura incongruens* (*Sein*), *S. sella* (*Sese*), *Cushmanidea elongata* (*Cuel*), *Neocytherideis faveolata* (*Nefa*), individuals number (IND), species number (SPN).

ed in two subcluster Cl.1a and Cl.1b (Figs 6a and 6b). The first one contains the polyhaline-euhaline *Quinqueloculina seminula*, *Siphonaperta agglutunans* and *Siphonaperta aspera* with a relative abundance of 15%, 5% and 10% respectively from 280 to 90 cm. Cluster (Cl.1b) includes the polyhaline-euhaline *Quinqueloculina anectens, Adelosina longirostra, Spiroloculina tenuiseptata, Massilina secans, Siphoneperta irregularis, Triloculina tricarinata* (Fig. 6c). This maximal contribution of the species is observed between 280 to 160 cm depths. The exclusive presence of the polyhaline-euhaline species marks a lagoonal environment submitted to pelagic influences. Cluster 2 corresponding to lagoonal/marine assemblage contains the oligo-mesohaline to euryhaline species *Ammonia parkinsoniana* and *Ammonia tepida* with high rates of 60% and 30%, respectively, observed between 330 to 280 cm. The high contribution of species from Cl.2 is also observed from 160 to 35 cm. These are the oligo-mesohaline to euryhaline taxa *Ammonia beccari* and *Elphidium advenum* with a contribution of 30% and 20%, respectively. These species, present in the two intervals, indicate a lagoon submitted to fresh water influence for the first one and a closed lagoon for the second with minor fresh water impact. Single species are *Elphidium crispum*, *E. macellum* and *Quinqueloculina parvula*.

Core zones: In Core SM1, the variation of os-

Assemblage		Species	Autoecology	Reference
OSTRACODS ASSEMBLAGE	**Lagoonal/estuarine:** (Oligohaline-mesohaline to very euryhaline)	*Cyprideis torosa*	Euryhaline and eurythermic, quiet water, tolerates a stressed environment	Pascual & Carbonel 1992
			Punctuated specimens indicate oligohaline to polyhaline conditions	Carbonel 1980
			Common in brackish water	Montenegro & Pugliese, 1995, 1996
			Oligo-mesohaline exceptionally also polyhaline, prefer muddy or sandy substrates with plants. Survive in salinities up to 150 g/l	Wagner 1957; Ascoli 1967; Neale 1988; Lachenal 1989
			Tolerates a wide range of salinity (from 1 to 120 g/1) and variable temperature and oxygen conditions	Pint et al. 2012
			Typical brackish-lagoonal species	Trog et al. 2013
		Xestoleberis aurantia	Brackish water, recorded in coastal settings including intertidal pools	Carboni et al. 2002
			Brackish littoral species (oligo-mesohaline exceptionally also polyhaline) Prefer muddy or sandy substrates with plants	Mazzini et al. 1999
			Very euryhaline	Dolez et al. 2015
	Coastal/estuarine (Polyhaline-euhaline)	*Cytheromorpha fuscata*	Oligohaline-mesohaline	Dolez et al. 2015 ; Carbonel 1982
			Oligohaline-mesohaline to very euryhaline	Tiphaine et al 2016
		Aurila prasina	Polyhaline-euhaline, living on fine-grained substrates, frequently with *Posidonia*	Wagner 1957; Lachenal 1989
		Aurila convexa	Marine-brackish waters, adapted to agitated environments Colonize the mediolittoral and the upper limit of the infralittoral zone	Nachite et al. 2010
	Marine/brackish (Polyhaline-euhaline)	*Carinocythereis carinata*	Marine sub littoral species typically living on sand or silt. Substrates at depth of 2-60 m	Athersuch et al. 1989
		Semicytherura incongruens	Phytal marine, polyhaline-euhaline	Salel et al. 2016
			Marine	Marriner et al. 2012
		Loxoconcha elliptica	Phytal environments -hydrodynamic conditions Dominates near fluvial water suppliers	Oh & Carbonel 1978 ; Carbonel and Pujos 1981; Ruiz et al. 2000b; Salel et al. 2016
			Typical for brackish estuarine waters (salinity between 10 and 20 g/l). Prefers higher water energy conditions	Carbonel 1982; Zaïbi et al. 2012
			Estuarine to closed lagoon with high range of salinity	Frenzel et Boomer 2005 ; Lachenal 1989 ; Mazzini et al.1999
			Spans from 0.5 to 30 g/l very euryhaline	Dolez 2015
		Hiltermannicythere emaciata	Phytal marine, confined to shallower sub littoral marine conditions	Athersuch et al. 1989
		Loxoconcha rhomboidea	Phytal marine , shallow marine, polyhaline-euhaline	F. Ruiz et al. 2006 ; Dolez et al. 2015
		Leptocythere pellucida	Estuarine species	Pascual et al. 2002

Tab. 3 (continues on p. 529) - Autoecology summary of the prominent species of ostracods and benthic foraminifera assemblages founded along the core SM1 of the Younga Sebkha (Hachichina coast). All species and assemblages presented in this table are considered according the Cluster analysis dendrogram in R-mode.

FORAMINIFERA ASSEMBLAGES	**Coastal/marine** (Polyhaline-euhaline)	*Leptocythere fabaeformis*	Euryhaline, marine-brackish to marine, polyhaline-euhaline	Trog et al. 2015 ; Dolez et al. 2015 ; Salel et al. 2016
		Semicytherura sella	Phytal marine	Zaibi et al. 2016
		Leptocythere sp.	Euryhaline taxa, mesohaline to low polyhaline environment	Mazzini et al. 1999
	Lagoonal/marine (Oligohaline-mesohaline to very euryhaline)	*Ammonia parkinsoniana*	Common along the Italian coast and at the mouths of rivers	Di Bella et al. 2008
			Abundant in lagoons	Almogi-Labin et al. 1992
			Euryhaline waters in association with A. tepida	Sarr et al. 2009
			Indicative of shallow water depths, variable salinity and fluvial influence	Osterman et al. 2009
		Ammonia tepida	Reflects the extreme hypersaline conditions. High water temperature in the internal edge of the lagoon	El Kateb et al. 2018
		Ammonia beccari	Hyposaline lagoons and estuaries, very frequent among sandy sediments in inner shelf environments, euryhaline species.	Murray 1971; Carbonel & Pujos 1981
			Cold temperate-tropical, anoxic-oxic neritic-baythal, hypersaline tolerant, pollution tolerant, opportunistic, Polar -tropical, hypoxic- oxic, mud association, high organic flux	Reymond et al. 2014
		Elphidium crispum	Marine and occurs in the littoral zone of the sea. It is commonly found creeping out on sea weeds	Kotpal 2008
			Oxic, hypersaline, pollution tolerant, seagrass and reef habitat, opportunistic	Reymond et al. 2014
		Elphidium advenum	Prefers the waters rich in nutrient in the mouth of the Po and tolerates environmental stress	Jorissen 1988 ; Di Bella et al. 2008
	Marine (Polyhaline-euhaline)	*Quinqueloculina seminula*	Marine to coastal, abundant in inner shelf environments, extending in mid shelf depths or outer parts of tidal inlets. Shallow-water and prodeltaic environments Mediterranean lagoons, marshes and continental shelves	Seeliger et al. 2017 ; Murray 1971 ; Hayward et al. 1999 ; Jorissen 1987 ; Langlet et al. 2014
			Hypoxic, tropical reef, lagoon and marsh habitat, epifaunal - infaunal, neritic-baythal	Reymond et al. 2014
		Quinqueloculina annectens	Highest salinity	Donnici et al., 1997
		Quinqueloculina parvula	An infralittoral – upper circalittoral species, tolerating heavy metal pollution characterized by the highest salinity	Sgarrella & Zei 1993 Frontalini & Coccioni 2011 Carboni et al. 2002
		Quinqueloculina lamarckiana	High-energy shelf (0-20 m). Widely reported in coastal environments with a strong marine influence	Narayan & Pandolf 2010
		Triloculina tricarinata,	Clear water, normal-marine to hypersaline conditions	Narayan & Pandolfi 2010
		Adelosina longirostra	Common in the infralittoral and upper circalittoral zone of the Mediterranean	Sgarrella & Moncharmont 1993
		Massilina secans	Open marine	Leorri & Cearreta 2004
		Siphonaperta aspera	Epiphytic and epifaunal genera	Vidovic et al. 2014
		Elphidium macellum	Marginal to upper circalittoral, mainly infralittoral species which tolerates low salinity waters	Oflaz 2006 ; Sen Gupta et al. 2009 ; Murray 2014 ; Pillet et al. 2013

Tab. 3 - Autoecology summary of the prominent species of ostracods and benthic foraminifera assemblages founded along the core SM1 of the Younga Sebkha (Hachichina coast). All species and assemblages presented in this table are considered according the Cluster analysis dendrogram in R-mode.

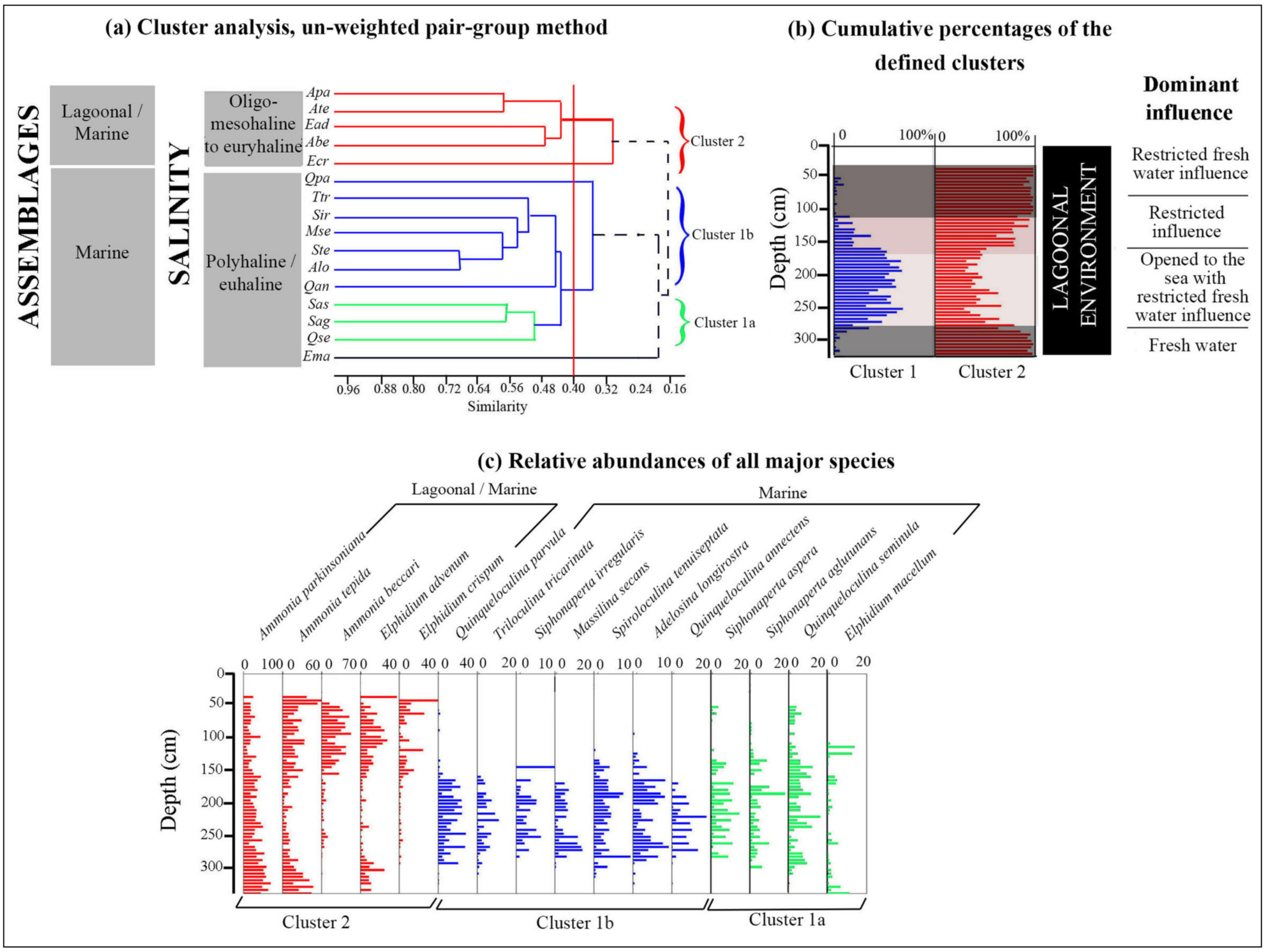


Fig. 6 - a) R-mode cluster analysis performed on the 16 fossilized major foraminifera species (> 10% in at least one) of the 65 investigated samples showing the clusters Cl.1, Cl.2 and the sub-clusters Cl.1a, Cl.1b. b) Cumulative percentages of taxa composing the defined clusters along core SM1. c) Relative abundance of all major species along core SM1.

Foraminifer taxa abbreviations: *Ammonia parkinsoniana* (*Apa*), *A. tepida* (*Ate*), *A. beccari* (*Abe*), *Elphidium crispum* (*Ecr*), *E. advenum* (*Ead*), *E. macellum* (*Ema*), *Quinqueloculina parvula* (*Qpa*), *Q. annectens* (*Qan*), *Q. seminula* (*Qse*), *Siphonaperta irrigularis* (*Sir*), *S. agglutunans* (*Sag*), *S. aspera* (*Sas*), *Spiroloculina tenuiseptata* (Ste), *Triloculina tricarinata* (*Ttr*), *Massilina secans* (*Mse*), *Adelosina longirostra* (*Alo*), individuals number (IND) and species number (SPN).

tracod and benthic foraminifera taxa, coupled to their species richness and relative abundances along SM1 core allowed us to distinguish the following zones (Fig. 7): Zone I, from 330 to 310 cm, is characterized by the dominance of the lagoonal/estuarine ostracod association (40%) coupled to marine/brackish taxa (50%) and coastal estuarine species (10%) in coarse silts. It shows the presence of the euryhaline species *C. torosa*, *L. elliptica,* the taxa typical of estuarine environment showing high water energy (Carbonel, 1982; Ruiz et al. 1996) and the oligo-mesohaline *C. fuscata* (Pascual & Carbonel 1992). The foraminifera reveal the dominance of the lagoonal/marine association (95%) containing the estuarine taxa *A. parkinsoniana* and *A. tepida.* Zone II, from 310 to 290 cm, records the first appearance of macrofauna and the diversification of ostracods and foraminifera. It reveals the appearance of the coastal/marine association (15%) constituted by the polyhaline-euhaline *Semicytherura sella*, *Neocytherideis faveolata* and *Leptocythere* sp. coupled to the marine/brackish association (60%) constituted by *L. elliptica*, more frequent than in the previous zone and the two phytal polyhaline-euhaline *Loxochoncha rhomboidea* and *Semicytherura incongruens.* It reveals the depletion of the lagoonal estuarine association (10%), where *X. aurantia* substitutes *C. torosa,* and coastal/estuarine taxa (15%) such as the estuarine *Cytheromorpha fuscata* and *Aurila convexa.* It shows the dominance and persistence of the lagoonal/marine foraminifera (95%) constituted by *A. parkinsoniana* and *A. tepida* associated to the most

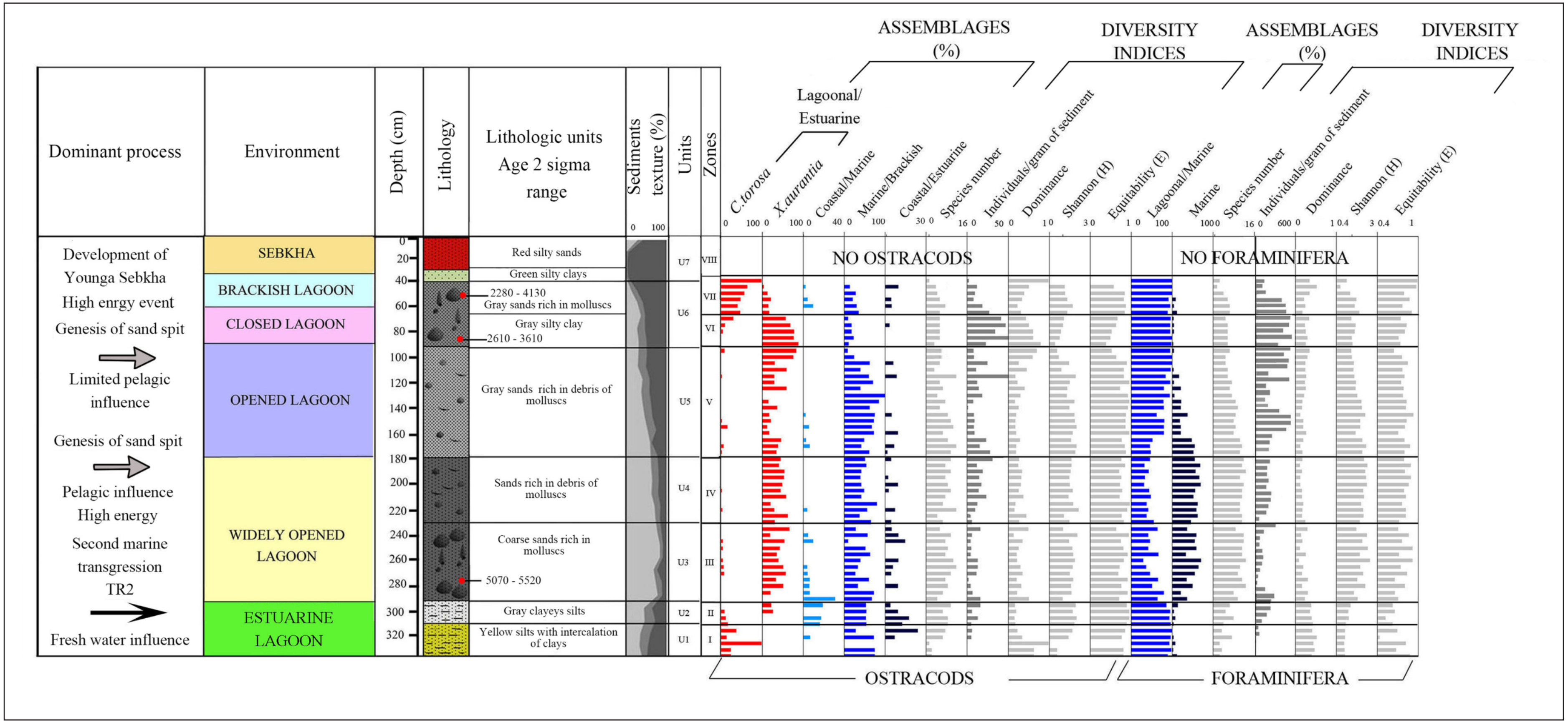


Fig. 7 - Sedimentologic and microfaunistic (ostracods and benthic foraminifera) data of SM1 core. Dominant process, environments, lithological column and units, calendar age, sediment texture, zones, vertical distribution of assemblages, individuals number/gram, species number and diversity indices.

reduced values of the indices H and E. This interval is also characterized by the increase of the species number and density of ostracods and foraminifera. Zone III, from 290 to 230 cm, is rich in gastropods and bivalves 5070-5520 cal yr BP in age. The ostracod associations reveal the enhancement of the lagoonal/estuarine taxa (40%), represented exclusively by the euryhaline *X. aurantia,* associated to the marine/brackish species (50%) containing the polyhaline-euhaline *L. rhomboidea*, *C. carinata* and *C. elongata*. The coastal/estuarine and coastal/marine taxa have a similar abundance of 5%. Characterized by the improvement of species number, the ostracofauna also show the increase of H and E index values. Zone III is also distinguished by the depletion of the lagoonal/marine foraminifera association (55%) coupled with the remarkable enrichment of marine taxa (45%) represented essentially by the appearance of the polyhaline-euhaline *Quinqueloculina parvula*, *Q. annectens*, *Q. aspera* and *Adelosina longirostra*. From the base to the top of the interval, the foraminifera species number and diversity indices H and E record high values and are associated with the reduction of the density. In Zone IV, from 230 to 180 cm, the ostracofaune is characterized by the disappearance of coastal/marine taxa and the depletion of coastal/estuarine species associated to the enhancement of marine/brackish and lagoonal/estuarine associations. The individual number reaches 25 individuals/gram of sediment. The foraminifera shows comparable association rates then the zone III with the enrichment of the marine species *Quinqueloculina parvula*, *Spiroloculina tenuiseptata* and *Adelosina longirostra* and a high value of the individual number reaching up to 150 individuals/gram of sediment. Zone V, from 180 to 90 cm, differs from the previous zone by the depletion of lagoonal/estuarine and the enrichment of marine/brackish ostracods reaching 60%. The upper part of zone V shows the increase of lagoonal/estuarine ostracods, reaching 90%, coupled to the reduction of the marine/brackish taxa. The zone V is also marked by the reduction of ostracod species richness and of the H and E diversity indices coupled with the high values of individuals number. This interval shows the increase of the lagoonal/marine foraminifera, which reaches up to 100%, the reduction of the species number and the diversity indices H and E and the increase of foraminifera density. Zone VI, from 90 to 60 cm, 2620-3610 cal yr BP in age, is marked by the enhancement of lagoonal/estuarine ostracod (85%), represented by *X. aurantia*, the depletion of marine/brackish species and a drastic enrichment of ostracods density in its upper limit. This zone reveals the enhancement of the lagoonal/marine association reaching 95%, containing *A. parkinsoniana*, *A. tepida* and *Elphidium crispum*. The foraminifera give a high number of individuals and their species number continues to decrease. Zone VII, from 60 to 40 cm, is made up of sands rich in lagoonal molluscs (2280-4130 cal yr BP in age) and lithoclasts. It records the enhancement of the lagoonal/estuarine ostracods, reaching 100%, which reveals the appearance of the euryhaline *C. torosa* (substituting gradually *X. aurantia*) and *L. elliptica* and the reduction of ostracod diversity and density. The enrichment of the marine/brackish, the recurrence of the coastal/estuarine and coastal marine ostracods and the highest values of density mark the limit between the zones VI and VII. The autochthonous origin of the lagoonal/estuarine ostracod species is evidenced by the presence of the juvenile and adult forms. However, the marine/brackish and coastal/marine species are characterized by either juvenile or adult individuals, in fragments, showing their transport, corresponding thereby to a taphocoenose of high energy. In addition, the molluscs of this interval show a dissolved and corroded surface. The zone VII shows the dominance of lagoonal/marine foraminifera, as in the zone VI, reaching 100% and the decrease of their species and individual numbers. Zone VIII, from 40 cm to the surface, is characterized by the absence of foraminifera, ostracods and molluscs.

Core SM2 (Fig. 8): Zone I, from 105 to 85 cm, is distinguished by the dominance the marine/brackish association (50%), containing the dominant polyhaline-euhaline *Loxoconcha rhomboidea* and *Semicytherura incongruens,* associated to the coastal/marine taxa (30%), such as *Leptocythere* sp. and *Semicytherura sella*, and lagoonal/estuarine association represented by *X. aurantia* (15%). The species number does not exceeded 10 taxa and is associated with reduced values of density. The foraminifera show the dominance of lagoonal/marine association (95%), revealing the dominant taxa *A. beccari* and *E. advenum*. The lowest values of foraminifera density and diversity indices H and E mark this interval where the species number varies between 6 and 8.

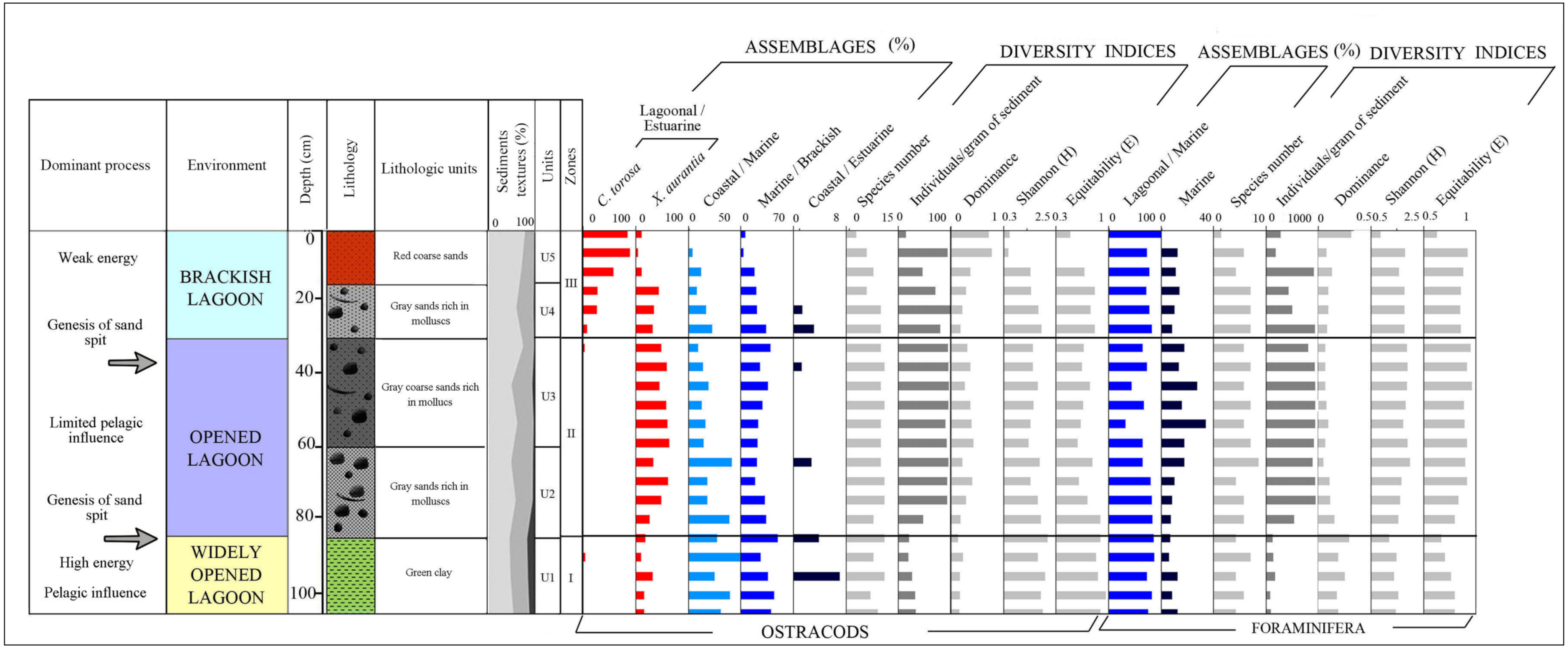


Fig. 8 - Sedimentologic and microfaunistic (ostracods and benthic foraminifera) data of SM2 core. Dominant process, environments, lithological column and units, calendar age, sediment texture, zones, vertical distribution of assemblages, individuals number/gram, species number and diversity indices.

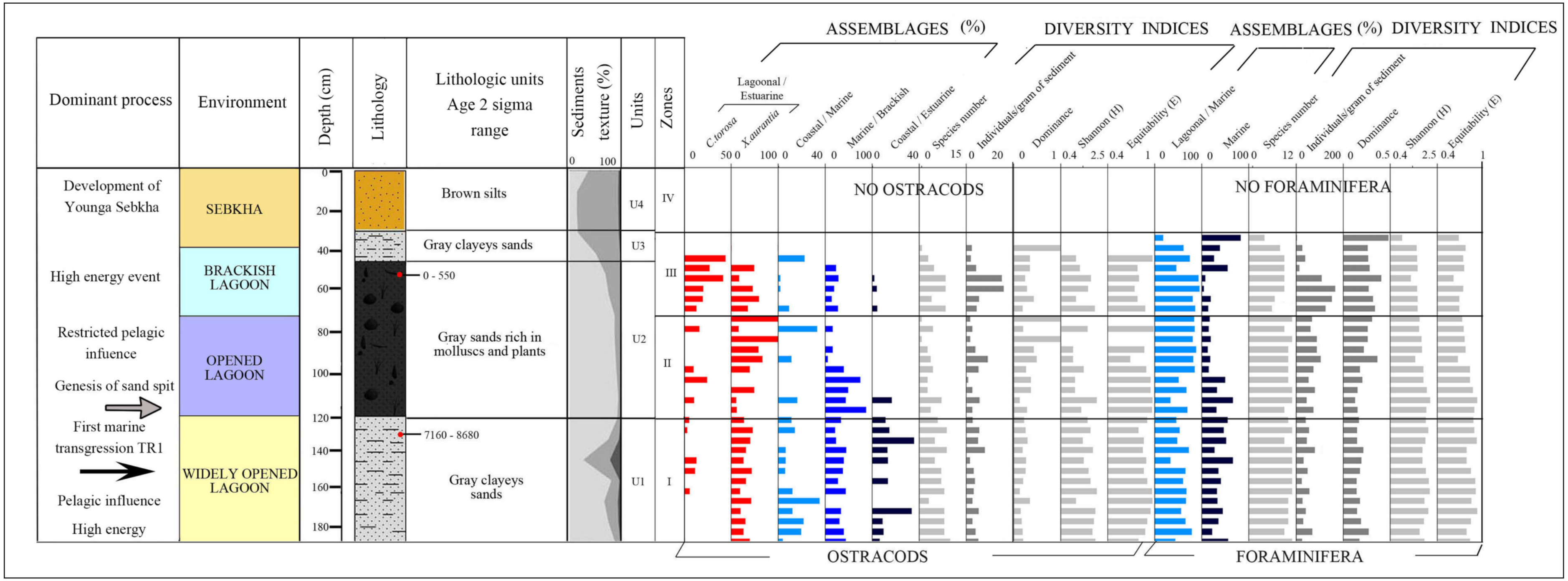


Fig. 9 - Sedimentologic and microfaunistic (ostracods and benthic foraminifera) data of SM3 core. Dominant process, environments, lithological column and units, calendar age, sediment texture, zones, vertical distribution of assemblages, individuals number/gram, species number and diversity indices.

Zone II, from 85 to 30 cm and made up by sands rich in molluscs, is characterized by the enrichment of the lagoonal/estuarine ostracods (55%) associated with the decrease of the coastal/marine and marine/brackish taxa. *X. aurantia* is the dominant taxa (65%). The highest values of ostracod density along the core are also observed in this interval. The zone II is also marked by the depletion of the lagoonal/marine foraminifera (75%) and by the highest values of density along the core. Zone III, from 30 cm to the surface, is marked by the development of sands rich in lagoonal molluscs. It reveals the reduction of the density, the species number and the two diversity indices (H and E) of ostracods. It is also distinguished by the dominance of the lagoonal/estuarine ostracods, which reach 100 % in the top of the interval, and the first apparition of the euryhaline *C. torosa* in the core. The enrichment of the lagoonal/marine foraminifera, reaching 90% where the euryhaline species *A. tepida* and *A. parkinsoniana* are dominant, is coupled to the decrease of species richness and density.

Core SM3 (Fig. 9): Zone I, from 185 to 120 cm, made up by fine clayey sands (U1), 7160-8680 cal yr BP in age, is marked by the dominance of the two assemblages marine/brackish (45%) and lagoonal/estuarine (35%), associated with the coastal/estuarine (10%) and coastal/marine taxa (10%). It reveals important values of species richness and density. The high values of the diversity indices H and E indicate a rich population where the individuals are equitably distributed among species. The lagoonal/marine foraminifera, mainly represented by *Ammonia tepida* and *A. beccari*, are dominant (70%). This zone is characterized by high values of species richness and of H and E diversity indices and reduced density values. Zone II, from 120 to 75 cm; shows, from the base to the top, the enhancement of lagoonal/estuarine taxa reaching 80%. This zone is also characterized by the reduction of the species richness and density. The decrease of the H and E indices indicates an unstructured population where the individuals are inequitably distributed among the species. The lagoonal/marine foraminifera reach 90% in the upper part of the zone associated to the increase of the individual number and the reduction of H and E values. Zone III, from 75 to 30 cm, is represented by sands and clayey sands characterized by their richness in *Posidonia* sp., bivalves and gastropods, such as *Cerastoderma glaucum* and *Cerithium vulgatum* (0-550 cal yr BP in age). It is distinguished by the increase of lagoonal/estuarine ostracod taxa (70%) revealing the improvement of the euryhaline *Cyprideis torosa* and the depletion of *X. aurantia*. The foraminifera show a comparable percentage of lagoonal /marine taxa as in the zone II. The middle part of the zone, at 60 cm depth, is marked by the abrupt recurrence of the marine/brackish and of coastal/estuarine ostracods associated to the high values of density and ostracods species richness. Different aspects observed through the foraminiferal tests of robust taxa (breaking of the last chambers, abrasion of the external ornamentation) plead for an important transport process. All these parameters mark the recurrence of pelagic influence and reveal a high-energy event towards 0-550 cal yr BP. Zone IV, from 30 cm, is formed by brown clays without fauna.

Core SM4 (Fig. 10): Zone I, from 130 to 95 cm, is made up of gray silts. The dominant marine/brackish ostracod association (60%), containing the estuarine *L. elliptica*, the polyhaline-euhaline *Leptocythere fabaeformis* and *Aurila woodwardii*, is associated to lagoonal/estuarine (15%), coastal/estuarine (15%) and coastal/marine (10%) taxa. The density and species number of ostracofaune are the most reduced of the core. The zone I records the dominance of the lagoonal/marine foraminifera association reaching 95%, represented essentially by the estuarine taxa *A. parkinsoniana*, the reduced values of species number and an important density reaching 1500 individuals/gram of sediment. Zone II, from 95 to 60 cm, is built up by fine sands characterized by their richness in molluscs. The lagoonal/estuarine ostracods reach 40% and are associated to the depletion of marine/brackish (45%) and coastal/estuarine (5%) taxa. This interval is also marked by the increase of species richness and density. The marine foraminifera taxa, reaching 5%, are represented by *Elphidium simplex* and *Quinqueloculina seminula*. However, the density and the species number of foraminifera increases slightly. In Zone III, from 60 to 35 cm, the lagoonal/estuarine ostracods taxa are further dominant reaching 70% and associated to the depletion of marine/brackish, coastal/marine and coastal/estuarine taxa. The ostracofauna records a high density and a reduced species number. To the top of the interval, *X. aurantia* is more reduced and gives

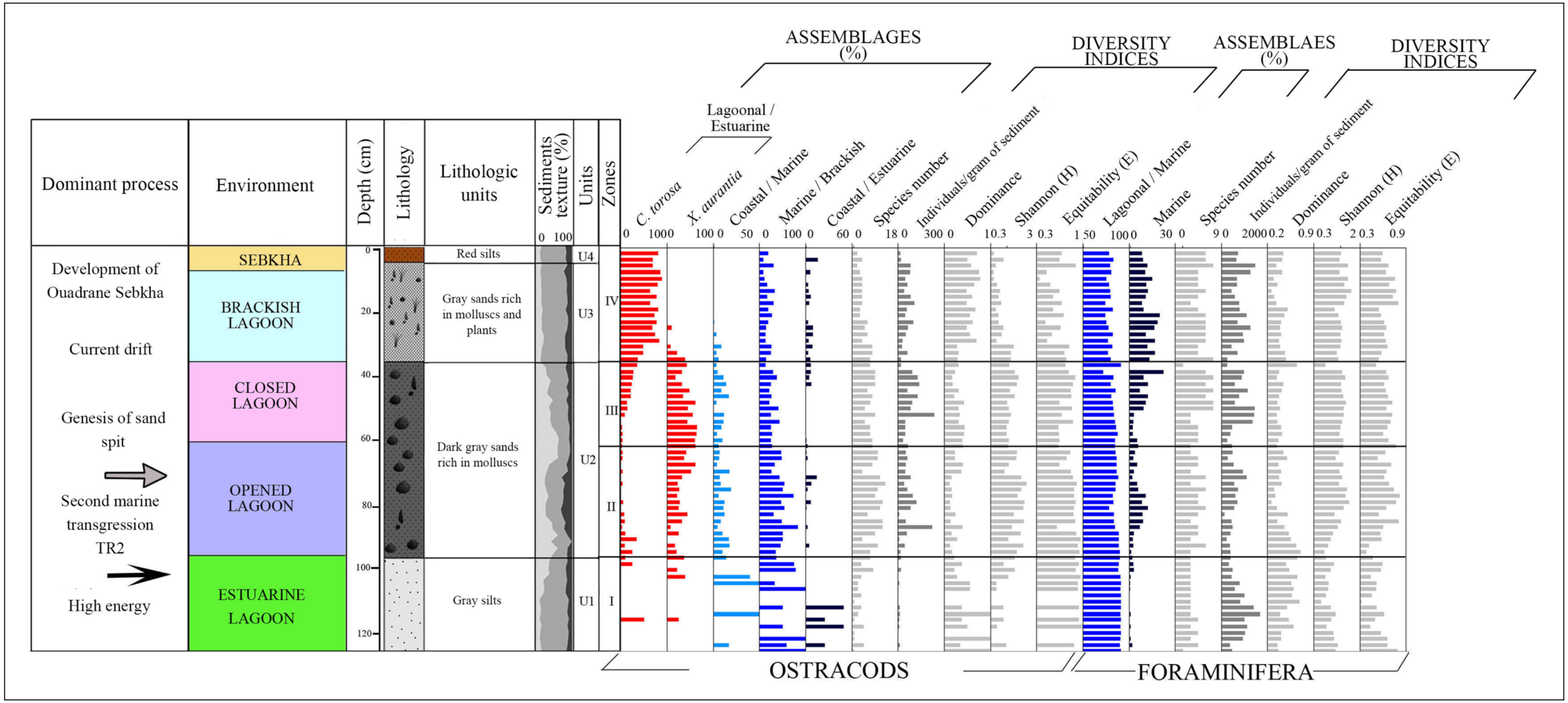


Fig. 10 - Sedimentologic and microfaunistic (ostracods and benthic foraminifera) data of SM3 core. Dominant process, environments, lithological column and units, calendar age, sediment texture, zones, vertical distribution of assemblages, individuals number/gram, species number and diversity indices.

way to euryhaline *C. torosa*. The marine foraminifera, poorly represented in the lower part of the zone, show an increase of their percentage to the top coupled to the high values of individuals and species number. Zone IV, the last 35 cm, is rich in bivalves and vegetal debris in poorly-sorted sand (U3) and records the enrichment of the euryhaline *C. torosa*, reaching 80%, coupled with the depletion of the marine/brackish taxa (10%) and the disappearance of the coastal marine species and the decrease of ostracods species number and density. It records the enhancement of lagoonal/marine (55%) and the depletion of marine taxa to the top (45%). A punctual increase of the marine/brackish ostracods and marine foraminifera, a high value of species number and density of the ostracofauna and foraminifera mark the middle part of the zone IV. In addition, the molluscs have abraded shells and disarticulated valves associated to dissolved and corroded foraminifera tests. All these parameters corroborate a high energy deposit.

Discussion

Palaeoenvironmental reconstruction

Through the results of palaeontological, sedimentological and geochronological analyses, we could reconstruct the changing palaeovironement within the investigated Hachichina wetland and compare this evolution with Mediterranean coast. In the following section, the evolution of the investigated area is discussed in three levels: i) The early Holocene pre-transgressional bedrock; ii) Sea-level rise and genesis of the sand spit; and iii) phase of sand spit genesis and high energy event.

The early Holocene pre-transgressional bedrock. Investigations of Morzadek (2002) showed the establishment, in the West of the Gulf of Gabes, of sebkhas at the isobaths -25, -28 m, between 28.340 and 21.120 cal yr BP, a marine environment at -75 m, around 12.580 cal yr BP and a transgression which invaded the gulf of Gabes from 9.930 cal yr BP. For Goy et al. (1996), the deceleration of relative sea-level rise took place in the Mediterranean coast at 10.000 cal yr BP. Lambeck et al. (2014) note a decrease in the rate of sea level rise from 8.2 kyr to 2.5 kyr BP, after which ocean volumes remained nearly constant until the renewed sea-level rise at 100-150 yr ago, with no evidence of oscillations exceeding 15-20 cm in time intervals ≥200 yr from 6 to 0.15 kyr BP. Zaibi et al. (2016) considered that the oldest sediments of Southern Skhira coast are represented by early holocene continental sands and clays. However, at Kneiss Island, the substratum is constituted by Tyrrhenian sands rich with molluscs (Gargouri 2009). In the Sebkhas Younga and Ouadrane, by means of the different cores, two old subsurface sediments reached are Middle Holocene in age (Fig. 11). The first one relates to the unit U1 (SM3 core), corresponding to clayey sands > 7160-8680 cal yr BP in age. The second one corresponds to the unit U1 (SM1 core) made up by yellow sands with intercalations of clays > 5070-5520 cal yr BP in age.

Sea-level rise and genesis of the sand spit. The first marine transgression (TR1) took place towards 7160-8680 cal yr BP. It is limited in the southern part of Younga Sebkha and recorded at SM3 core (zone I, unit U1) by the widely opened lagoon environment, with the dominance of lagoonal/marine foraminifera (70%) and high values of species richness and diversity indices H and E (Figs 11 and 12). The opening of the environment to the sea is also proved by the ostracofauna revealing the dominance of the lagoonal/estuarine (35%) associated to marine/brackish (45%) taxa and high values of species number, density and diversity indices H and E. The high energy is revealed by the very poorly sorted grains transported by suspension and rolling process. Under a context of rising sea level, and at Skhira Southern coast, studied by our team and published by Zaibi et al. (2016), the continental Holocene sands and clays were overlaid by a widely opened lagoon biofacies rich in marine ostracods and foraminifera recording a transgressive event towards 7460 cal yr BP. For the same period, Lakhdar et al. (2006) describe, in Boujmel Sebkha, marine sands 7445 cal yr BP in age. This first marine flooding, TR1, coherent with delta initiation recorded throughout the circum Mediterranean (Stanley & Warne 1994; Anthony 2009), is also recognized between 8.7-7.5 cal kyr BP in the Spanish coast (Marco-Barba et al. 2013). A period of wetter conditions was registered in the Sahara and Sahel, from 9.5 to 7.0 cal kyr BP (Damnati 2000) and the genesis of freshwater carbonate structures in the hyper-arid Gebel Uweinat (Egypt), between 9.4 and 8.1 cal kyr BP, is mentioned by Margarita et al. (2014). In Northern Spain coast, modern estuaries began to develop around 8.5 cal kyr BP (Leorri & Cearreta 2004). In Central Tunisia, the improvement of environmental conditions were detected, such as in Maknassy from 10 to 7 cal kyr BP (Ouda et al. 1998), in Kasserine area from 7.5 to 7.2 cal kyr BP (Zarai 2006), in Jebel Goubrar-Khechem (Amami 2010) from 8.0 to 7.5 cal kyr ? BP and in Gafsa area, from 8.790 to 3.230 cal kyr BP in age (Henchiri 2014).

The second marine transgression (TR2) 5070-5520 cal yr BP in age. TR2 is recorded in the cores SM1 (zone III, unit 3), SM2 (zone I, unit 1), SM3 (lower part of zone II, unit 2) and probably SM4 (zone I, unit 2) (Figs 11 and 12). More important than TR1, it allows the settlement of a widely opened lagoon, which covers the two sebkhas. TR2 is marked, in SM1 core, by a large size of quartz grains, poorly sorted sands rich in molluscs, the dominance of lagoonal/estuarine ostracods (40%) and marine/brackish taxa (50%) and the increase of species number. The enrichment of the marine foraminifera, the high values of the species number and of the diversity indices mark the importance of the pelagic influences and the opening of the environment to the sea. The suspension and rolling process grains transport indicates the high energy. The installation of this widely opened lagoon environment follows an estuarine background (zone I, SM1 core and zone I, SM4 core). The latter reveals a ponding of freshwater runoff from the hinterland plain behind Younga and Ouadrane Lagoons to produce the brackish water conditions. This environment allowed the dominance of the euryhaline taxa *L. elliptica*, typical of estuarine environment and high water energy associated to the estuarine foraminifera *A. parkinsoniana* (60 %), which reflects the impact of the Ouadrane and Younga watercourses and the dilution of marine waters.

Around 5500 cal yr BP, El Melah Sebkha (South of Gulf of Gabes) was invaded by a sea whose level was 2 m higher than the current one and marked by shell accumulations (Perthuisot 1975). For the same period, Zaibi et al. (2011) describe a closed lagoon at Southern Skhira coast, which records a step of opening towards 5408 cal yr BP synchronous with the transgressive event TR2, reported herein at the Younga Sebkha. Jedoui et al. (1998) report, on Jerba coast, bioclastic deposits covering the range 5900-4000 yr BP, located at altitudes varying between +40 and +100 cm, as well as marine deposits, 2100 yrs BP in age, positioned at the same level of the sea. The regularity of the marine deposits, having the same age, with respect to the sea level confirms for these authors the absence of tectonics. They conclude that the elevation, realized between 5900 years BP and 2000 years BP, would have a hydro-isostatic origin. However, for Morhange and Pirazzoli (2005), the emersion of Jerba coastal fringe would have reached a higher altitude of 186 cm and would be produced from 6000 years and stopped around 5000 years ago. However Vacchi et al. (2015) note that in the western Mediterranean, RSL rose continuously for the whole Holocene with a sudden slowdown at 7.5 kyr BP and a further deceleration during the last 4 kyr BP; after which time, observed RSL changes are mainly related to variability in isostatic adjustment. The sole exception is southern Tunisia, where data show evidence of a mid-Holocene high-stand compatible with the isostatic impacts of the melting history of the remote Antarctic ice sheet. On the other hand, Bedir et al. (1995) and Ghribi (2010), based on a seismological study, identified several active faults, directed N120, which affected Hachichina wetlands, delimit Ouadrane valley and continue in Mediterranean Sea. They note the importance of the neotectonic in Skhira area. Thereby, the second transgression event (TR2) can be attributed to the subsidence of the basement Skhira coast, a behavior favored by the reactivation of these faults.

Phase of sand spit genesis and high-energy event. The evolution of the widely opened lagoons to the present sebkha, by passing successively through an opened lagoon, a closed lagoon and a brackish lagoon can be explained by the genesis of sandy spits. This evolution is proved by the decrease of species richness, the enhancement of lagoonal/estuarine ostracod and lagoonal/marine foraminifera and the improvement of the densities (Fig.12). Also, the subsurface sediments show significant changes in element ratios profiles, influenced, in particular, by a substantial variations in the values of fluvial input proxies (K/Al) and of the terrigenous Fe/Al ratio (Fig. 13). Ouadrane Wadi discharge, during the estuarine lagoon period, would have mainly contributed clays from source regions, rich in illite and chlorite, leading to these increasing ratios. The reduced ratios of marine elements, Sr/Al and Cl/Al, during this period sign an estuarine lagoon submitted to fresh water influences and the dominance of brackish waters, as it is indicate by the

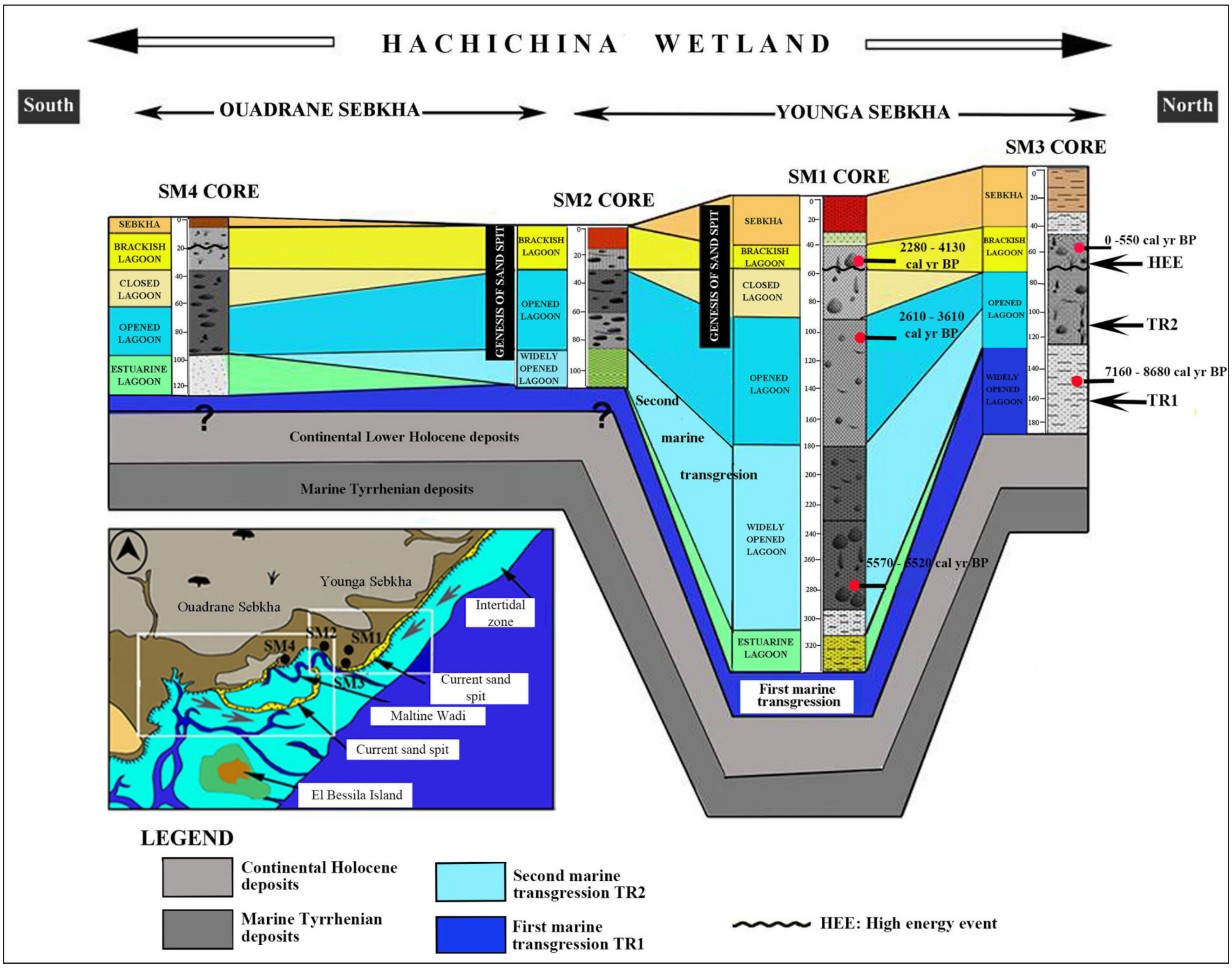
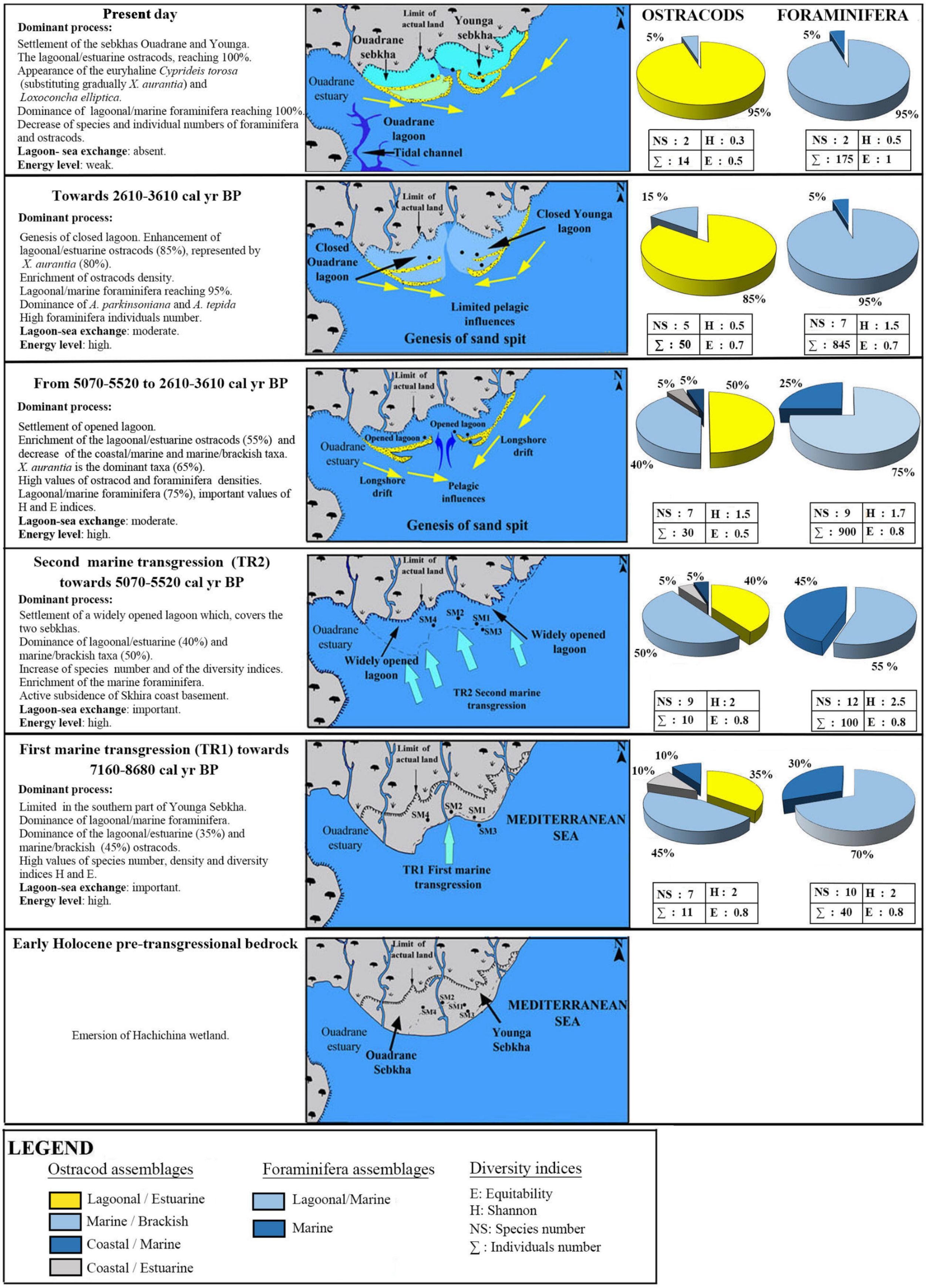


Fig. 11 - Correlation between the stratigraphy of Younga and Ouadrane Sebkhas. Transgressive episodes (TR1-TR2), period of sandy spit genesis and high-energy events.

oligo-mesohaline ostracods taxa. During the widely opened lagoon step, the increase of marine element ratios (Ca/Al, Sr/Al and Cl/Al) and the reduction of Fe/Al, suggest the importance of pelagic influence, subsequent to the marine transgression (TR1), the reduction of fluvial input and a variation in circulation intensity. Interestingly, most Cl/Al and Sr/Al values show distinct correlations with SiO_2/Al ratio and with the high values of species richness, suggesting that the detrital of quartz grain inputs are mainly of marine origin. During the progress of the opened lagoon to the closed lagoon, the reduction of marine/brackish ostracods and marine foraminifera correlated to the decrease of the SiO2 corroborate the marine origin of quartz grains (Fig. 13). The richness of the coast in SiO2 coupled with the action of the littoral current drift authorized the build-up of sandy spits in front of the estuaries and the genesis of lagoon that preserves a rich assemblage of euryhaline foraminifera and ostracod taxa. The sandy spits resulting in the closure of lagoons are still recognizable on satellite images. In fact, the presence of two recent sandy spits Younga and Ouadrane, oriented respectively to the South and to the North, reveal the importance of the present-day littoral drift. However, the fossilized ones, reaching up to 1 m and visible inside the two sebkhas, evidence current drift activity during Holocene time. In addition, the richness of the coast in quartz grains and the high energy are argued by the presence of ebb tidal delta, swash bars and mega ripples at the intertidal zones on southern side of Ouadrane Wadi mouth (Fig. 1B). The alongshore-oriented two sandy spits, prograding towards the South and the North, were probably developed from the action of the two Wadis of Ouadrane and



Present day

Dominant process:

Settlement of the sebkhas Ouadrane and Younga.
The lagoonal/estuarine ostracods, reaching 100%.
Appearance of the euryhaline *Cyprideis torosa* (substituting gradually *X. aurantia*) and *Loxoconcha elliptica*.
Dominance of lagoonal/marine foraminifera reaching 100%.
Decrease of species and individual numbers of foraminifera and ostracods.
Lagoon- sea exchange: absent.
Energy level: weak.

Towards 2610-3610 cal yr BP

Dominant process:

Genesis of closed lagoon. Enhancement of lagoonal/estuarine ostracods (85%), represented by *X. aurantia* (80%).
Enrichment of ostracods density.
Lagoonal/marine foraminifera reaching 95%.
Dominance of *A. parkinsoniana* and *A. tepida*
High foraminifera individuals number.
Lagoon-sea exchange: moderate.
Energy level: high.

From 5070-5520 to 2610-3610 cal yr BP

Dominant process:

Settlement of opened lagoon.
Enrichment of the lagoonal/estuarine ostracods (55%) and decrease of the coastal/marine and marine/brackish taxa.
X. aurantia is the dominant taxa (65%).
High values of ostracod and foraminifera densities.
Lagoonal/marine foraminifera (75%), important values of H and E indices.
Lagoon-sea exchange: moderate.
Energy level: high.

Second marine transgression (TR2) towards 5070-5520 cal yr BP

Dominant process:

Settlement of a widely opened lagoon which, covers the two sebkhas.
Dominance of lagoonal/estuarine (40%) and marine/brackish taxa (50%).
Increase of species number and of the diversity indices.
Enrichment of the marine foraminifera.
Active subsidence of Skhira coast basement.
Lagoon-sea exchange: important.
Energy level: high.

First marine transgression (TR1) towards 7160-8680 cal yr BP

Dominant process:

Limited in the southern part of Younga Sebkha.
Dominance of lagoonal/marine foraminifera.
Dominance of the lagoonal/estuarine (35%) and marine/brackish (45%) ostracods.
High values of species number, density and diversity indices H and E.
Lagoon-sea exchange: important.
Energy level: high.

Early Holocene pre-transgressional bedrock

Emersion of Hachichina wetland.

LEGEND

Fig. 12 - Hypothesized Holocene paleogeography of Hachichina wetland based on the results of this study focusing on the four cores used for ostracods and foraminifera analysis. Dominant process, energy level and pelagic influence during the main phases of Hachichina wetland evolution.

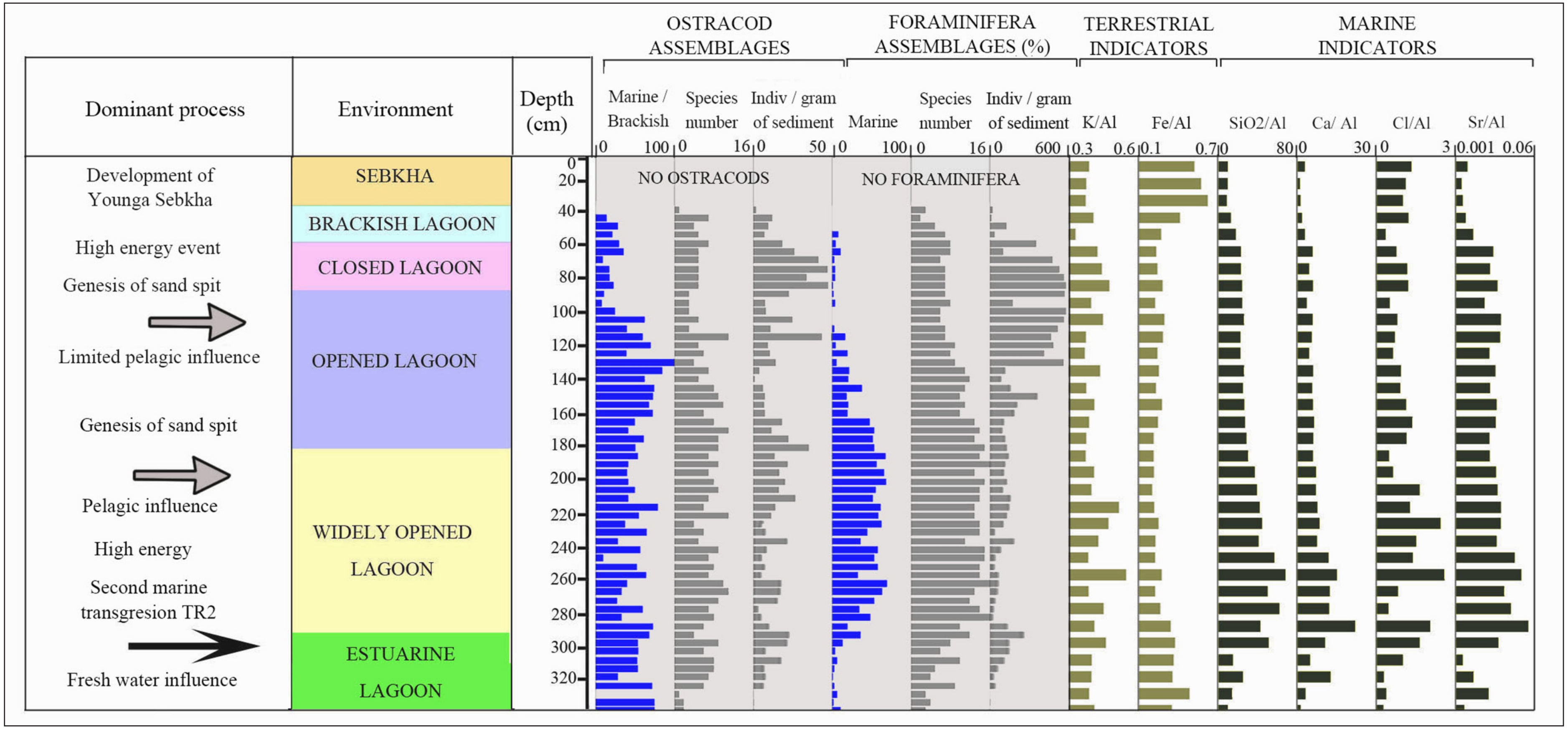


Fig. 13 - Geochemical data of SM1 core, Al-normalized concentrations of elements used as indicators of marine (Sr, Cl, Ca) and terrestrial (Al, Fe, K) trends, percentage of marine/brackish and marine assemblages, species number and individuals number of ostracods and foraminifera.

El Kebir, which enriched them as well in quartz grains during Holocene. These sandy spits allowed the genesis of a closed lagoon, towards 2610-3610 cal yr BP, progressing to a brackish one and finally evolving to the Younga and Ouadrane Sebkhas. However, and during the same time, a marine transgression is indicated by Zaïbi et al. (2012) towards 3005 cal yr BP in the southern coast of Skhira and by Paskoff & Sanlaville (1983) towards 2700 yr BP in Zarzis coast. The comparison of the behavior of Hachichina, Skhira and Zarzis coasts highlights the role played by the Ouadrane estuary during Holocene sedimentation. Actually, time shift of marine sedimentation is due to the building of sand spit and the genesis of sebkhas favored by the richness of the coast in quartz grains and the importance of drift current, unlike the South Skhira and Zarzis coasts, which record a marine transgression during the same time. Along the Gulf of Gabes during Holocene, the genesis of sand spit was mentioned in several sites such as Boujmel Sebkha between 6.8 and 4.0 cal kyr BP (Lakhdar et al. 2006), Bin El Oudiane Lagoon towards 5.0 cal kyr BP (Masmoudi et al. 2005), Dreiia Sebkha from 6671 cal yr BP (Zaïbi et al. 2016) and Northern Sfax Coast between 2018-2419 and 1001-1804 cal yr BP (Khadraoui et al. 2018). For the historical times, the action of drift currents was also quoted at Rass Dimas Lagoon by Amrouni (2008), at Chebba Sebkha by Zaïbi et al. (2016) and at Botria Lagoon by Kamoun et al. (2018), where it was responsible for a strong coastal accretion affecting the historic harbors, civilizations and allowing the genesis of lagoonal environments.

During the settlement of the brackish lagoon, following the genesis of sand spit, the abrupt enrichment of the marine/brackish, the recurrence of the coastal/estuarine and coastal/marine ostracods associated to the improvement of marine foraminifera and the high values of ostracods and foraminifera densities are observed, punctually, in the differents zones of the cores SM1 (zone VII), SM3 (zone III) and SM4 (zone IV). In addition, abraded mollusc shells and disarticulated valves are associated to the corroded foraminifera tests, the breaking of their last chambers and abrasion of the external ornamentation. However, a taphocoenosis of high energy is proved by the presence of marine/brackish and coastal/marine ostracod species characterized by each juvenile or adult individuals, in fragments. All these parameters suggest an important transport process following a high-energy event (0-550 yr cal BP in age) which may correspond to the extreme climatic event (0-250 yr cal BP in age) described in the South of Skhira coast by Zaibi et al. (2016) and reinterpreted as a tsunami event by Khadraoui et al. 2018. This event, breaking the sand spits, induced the introduction of marine coarse sands rich in a mixture of brackish and marine macrofauna and microfauna. It also explains the rework of coarse-grained sediments and the reversal of radiocarbon dates within the top layers of SM1 core.

Correspondence Analysis

Correspondence Analysis, applied to ostracod and foraminifera absolute abundances and sampling levels data, along with species number and density values as supplementary variables, was realized for the rich SM1 core. It shows clouds of points demonstrating a characteristic parabolic form, which marks an environment evolution.

Ostracods: The first two axes of the compromise analysis account for 24.09 and 19.05% of the total variability, respectively. Five groups can be distinguished (Fig.14). The first group, G1, positioned in the positive axis 1 and 2, contains the coastal/marine *Leptocythere* sp., *Neocytherideis faveolata* and *S. sella,* the oligo-mesohaline *Cytheromorpha fuscata* and the very euryhaline *L. elliptica.* This group represents the units U1 and U2 (zones I-II), reflects a high-energy event recognized by the descriptive analyzes and corresponds to an estuarine lagoon. The group G2, placed in the positive axis 2 and in the negative axis 1, includes the marine/brackish, polyhaline-euhaline taxa, *L. fabaeformis* and *L. pellucida* and the coastal/estuarine *A. convexa*, *Aurila sp.* G2 represents the zones II and III and characterizes the marine transgression (TR1) following the settlement of a widely opened lagoon proved in the micropalaeontological descriptive study. Group G3, located on the negative pole of the axis 1, includes the polyhaline-euhaline *S. incongruens*, *C. carinata*, *H. emaciata*, *L. rhomboidea*, *C. elongata* and *L. fabaeformis*. This group corresponds to the unit U5 (zone V) and indicates an opened lagoon. Group G4, situated in the positive pole of axis 1 and in the negative pole of axis 2, contains the individual number, the oligo-euryhaline *X. aurantia* and *L. pellucida.* It signs a closed lagoon, corresponding to the bottom part of the unit U6 (zone VI). The last group G5 positioned on the positive pole of axis 1 contains

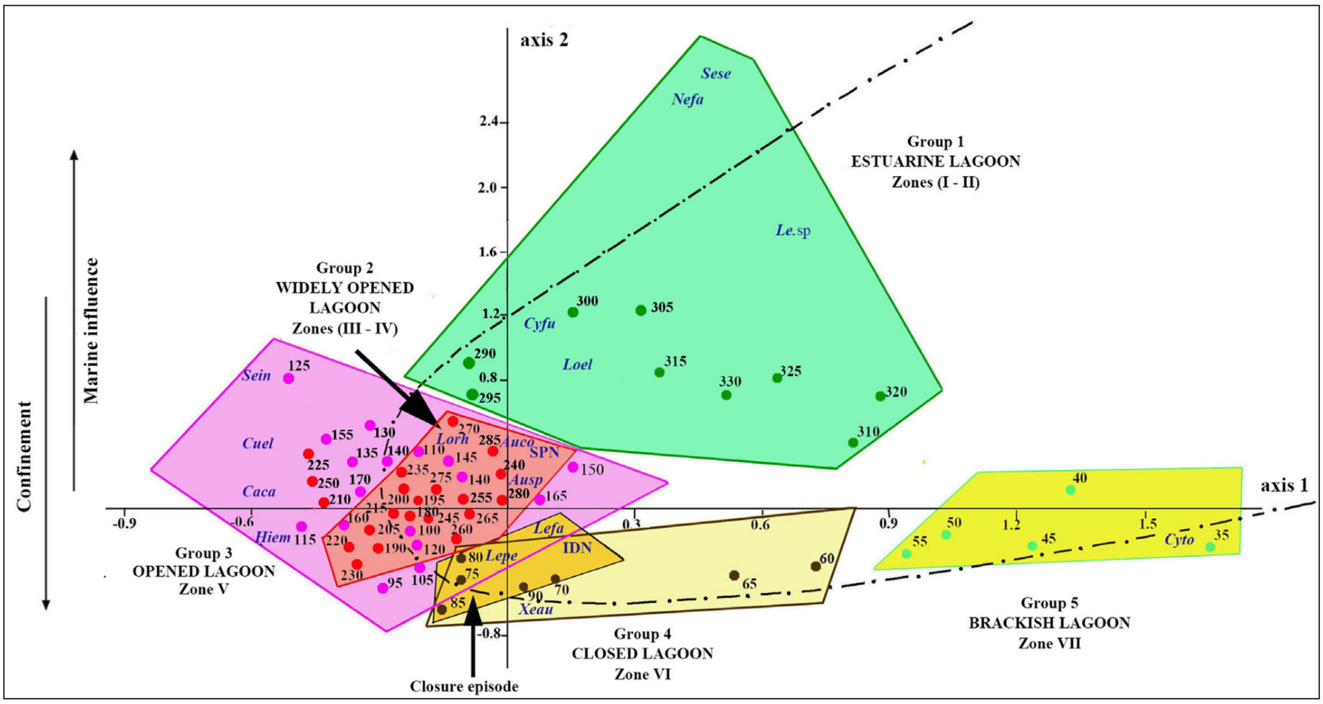


Fig. 14 - Factorial correspondence analysis. Projection of ostracods and samples data of SM1 core in the 1 x 2 factorial planes. Green points: samples from 330 to 290 cm, red points: samples from 290 to 180 cm, purple points: samples from 175 to 95 cm, brown points: samples from 90 to 60 cm and blue points: samples from 55 to 35 cm.
Ostracods taxa abbreviations: see figure 5, individuals number (IND), species number (SPN).

the euryhaline *C. torosa*. It corresponds to the settlement of the brackish lagoon, represented by the upper part of the unit U6 (Zone VII). Therefore, the axis 2, which acts as the confinement of the environment, shows an evolution from estuarine lagoon on its positive pole towards the actual sebkha on its negative pole. The transition between the two environments is made up by an intermediate widely opened, an opened lagoon and a closed lagoon.

Foraminifera: The first two axes of the compromise analysis account for 47.15 and 20.78% of the total variability, respectively. This analysis reveals four groups (Fig. 15).

Group G1, positioned in the positive axis 1 and composed of the lagoonal/ marine species *Ammonia parkinsoniana*, *A. tepida*, *Elphidium advenum* and the marine *E. macellum,* signs an estuarine lagoon (zones I-II). The group G2 contains the marine species *Quinqueloculina parvula*, *Q. annectens, Q. seminula*, *Siphonaperta agglutunans, S. aspera, S. irrigularis*, *Triloculina tricarinata*, *Masselina secans, Adelosina longirostra*, *Spiroloculina tenuiseptata* and the species richness. It has negative loadings on the axis 2 and positive ones on the axis 1. It corresponds to a widely opened lagoon (zones III-IV). Group G3, situated in the intersection of the two axes 1 and 2, contains exclusively the oligo-mesohaline to euryhaline taxa *A. beccari* and density. It corresponds to the zones V-VI and signs an opened lagoon evolving to a closed one. Group G4, located in the positive axis 1 and 2, contains the lagoonal/marine *E. crispum*. It marks the brackish lagoon (Zone VII), identified in the micropalaeontological descriptive. Therefore, the axis 2, which acts as the confinement of the environment, shows an evolution from estuarine/ widely opened lagoon on its negative pole towards the brackish lagoon on its positive pole. The alteration between the two environments is made up by an intermediate opened and closed lagoons (G3).

Holocene evolution of Hachichina wetland

Hachichina coast was endowed with several categories of wetlands (opened lagoon, closed lagoon and sebkha) during the holocene time. These wetlands recorded 1.0-3.5 m thick deposits containing good archives of landform evolution and environment changes. Holocene sedimentation was initiated towards 7160-8680 cal yr BP and is represented mainly by a fossiliferous sands and silts. Subsequent deposition of lagoonal sediments to brackish ones occurred in the upper Holocene. The

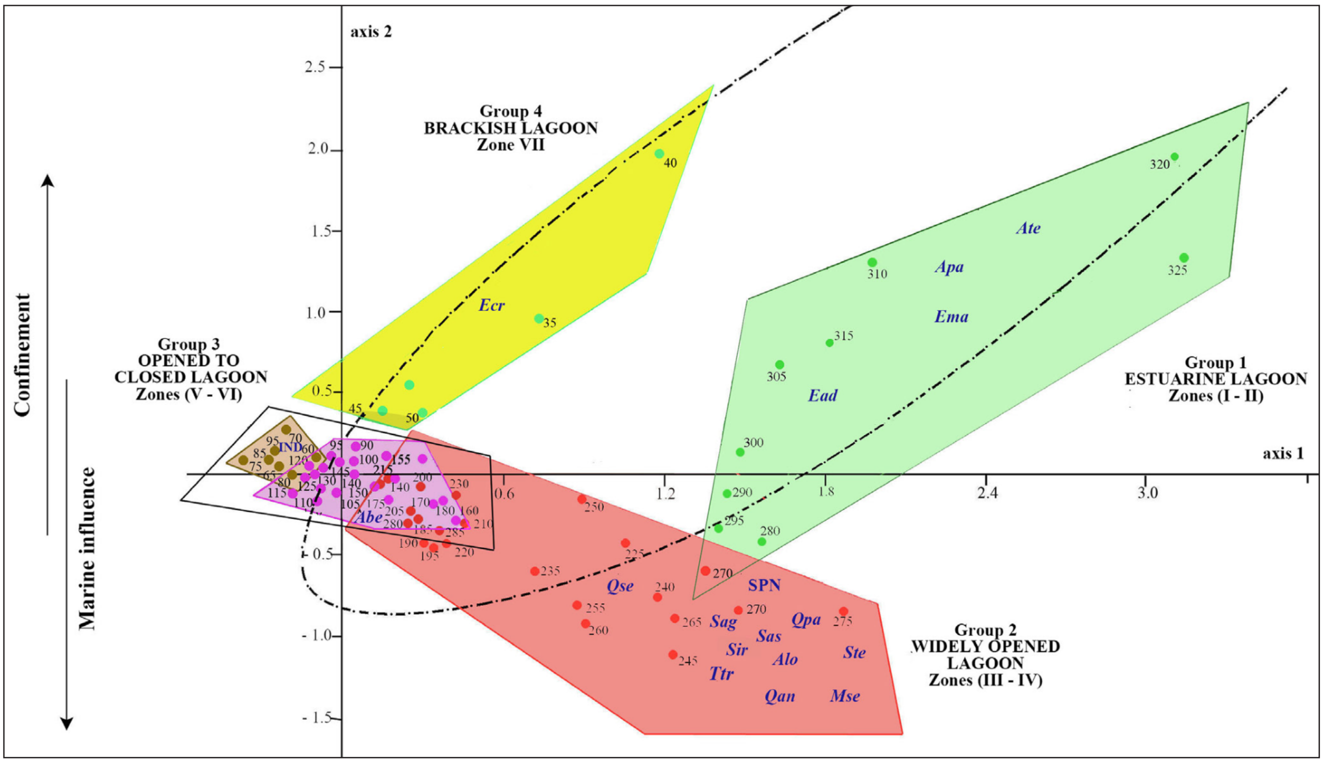


Fig. 15 - Factorial correspondence analysis. Projection of benthic foraminifera and samples data of SM1 core in the 1 x 2 factorial planes. Green points: samples from 330 to 290cm, red points: samples from 290 to 180 cm, purple points: samples from 175 to 95 cm, brown points: samples from 90 to 60 cm and blue points: samples from 55 to 35 cm. Foraminifer taxa abbreviations: see figure 6, individuals number (IND), species number (SPN).

proposed evolutionary succession reveals that many wetland bodies including Ouadrane and Younga Sebkhas evolved from the Ouadrane estuary. The upper arms of this estuary were cut off due to progradation of alluvial sediments during the late Holocene. In fact, after 5070-5520 cal yr BP, sediment supply was the key driver of salient morphogenesis and the genesis of sand spits. The latter controlled coastal dynamics, the closure of the lagoonal environment, toward 2610-3610 cal yr BP, and the genesis of the studied sebkhas. The relative sea-level curve herein deduced for Hachichina coast, appear in good agreement with the recent studies from the Gulf of Gabes region. In fact, and during the early Holocene, the rise of the sea level at approximately 7160-8680 cal yr BP at Hachichina coast allowed the settlement of a widely opened lagoon and at 7460 cal yr BP at Skhira where marine conditions contributed to the filling of this area with sands and silts. Towards 5070-5520 cal yr BP, a major transgressive phase, also recorded at Skhira and occurring during a time interval, characterized by an almost nil rate of sea level (Stanford et al. 2011) change, may be due to subsidence of the different study areas, such as Hachichina wetland grabens, and sediment compaction after the depositional process. All of them differ considerably from the glacio-hydro-isostatic model.

Conclusion

A multidisciplinary study of four cores taken from the Ouadrane and Younga Sebkhas (Hachichina wetland) allowed the reconstruction of the Holocene palaeoenvironmental evolution of this coastal area. An excellent correlation was found between ostracod and foraminifera palaeoecology, geochemical indicators and sediments characteristics.

These proxies indicate that the sedimentation in this wetland progressed as the result of the interaction between sea level rise, the discharge of Ouadrane Wadi leading to the formation of a sand spit after 5.0 cal kyr BP, the restriction imposed to circulation, mass exchanges and varying energy levels, and the neotectonic fault activation allowing the subsidence of the area. The studied cores represent a regressive sequence developed in a positive eustatic context. The lithology and microfauna of sediments accumulated in Hachichina wetland during the Holocene are mostly high-energy and reported to a lagoonal environment; subsequent flooding by the Holocene transgression drowned the inherited estuarine environment. The earlier stage of drowning formed a widely opened lagoon that evolved into a closed lagoon and finally into a sebkha, as a result of the development of a sand barrier that accompanied a marked decrease of the sea-level rise rate at that time. Since then, the sand spit has played a relevant role in the control of both the lagoonal dynamics and water salinity. In recent times, it has been progressively filled by continental sedimentation at the inner area and leading to the retreat of the continental lagoonal boundary. However, the Hachichina wetland remains subject to the effect of the relative sea level rise despite its protection through the genesis of the sandy spit. In fact, during exceptional tides and storms, the environment of the two sebkhas is drowned by the marine waters.

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