

THE ANTHROPOCENE AND GREAT ACCELERATION AS CONTROVERSIAL EPOCH OF HUMAN-INDUCED ACTIVITIES: CASE STUDY OF THE HALK EL MENJEL WETLAND, EASTERN TUNISIA

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Abstract. The Anthropocene covers the recentest period of globally widespread climate and environmental changes during which polluting human activities represent major risks for populations and their resources. The aim of this study is to investigate the drastic change in the sedimentary record of the sebkha Halk El Menjel, located in Tunisia, along a 10-cm long core to discuss the possible onset and limits of the Anthropocene and the Great Acceleration in this wetland. Sampling was carried out each 2 mm. According to the age-depth model and the increasing pattern of heavy metals content, we propose that the Anthropocene onset is located at ~300 yr BP. The increasing heavy metals content may be correlated to natural and/or anthropogenic sources such as volcanic eruptions and mining activities respectively. Also, the evolution of grain size percentages shows an increasing sediment flux during the Anthropocene and accentuated during the Great Acceleration. The principal component analysis shows three main groups of variables related to pollution, climate change and eustatism, indicating the combined effect of the natural and human induced activities during the Anthropocene. The evolution of microfauna shows that some microorganisms were influenced by the Anthropocene conditions whereas others remain indifferent.

Keywords: *Anthropocene, industrial revolution period, heavy metal pollution, western Mediterranean*

Introduction

Determining the full stretch of natural and anthropogenic pollution (and its causal link with climate variability) on spatial and temporal scales relevant to ecosystems functioning and human wellbeing is of utmost importance to anticipate the impact of, and improve the preparedness of communities to, future climate change. Most of coastal regions in Tunisia have been affected by different sources of pollution, which is well documented through the investigation of recent surface sediments (Gargouri, 2001; Ghannem et al., 2011, 2014; Wali et al., 2015; Zaaboub et al., 2015; Ennouri et al., 2016). Worldwide, this pollution dates back to the setting of mining and industrial activities during the Anthropocene and the subsequent Great Acceleration (GA) periods (Waters et al., 2014, 2016, 2018), which are, also, marked by drastic changes in climatic conditions (Hébert et al., 2017). Currently, the

Anthropocene is an under discussion geologic epoch dating back to the setting of noticeable human impact on terrestrial environments and the subsequent biotic conditions (Yusoff, 2013; Young et al., 2016). It has recently occupied the heart of earth sciences (Crutzen et al., 2006). In spite of the existence of signs of micropaleontological biomarkers characterizing this epoch (Wilkinson et al., 2014), until August 2016, neither the International Commission of Stratigraphy (ICS) nor the International Union of Geological Sciences (IUGS) have yet officially approved the term “Anthropocene” as a standalone subdivision of the geological timescale (Castree, 2017). Different Anthropocene bases (“beginnings”) were controversially proposed, because of the various disciplinary perspectives and criteria. First proposed by Crutzen and Stoermer (2000), the term “Anthropocene” covers the second half of the 20th century overlying therefore the Holocene in term of stratigraphy and geochronology. During this period, the global effect of human activities was clearly noticeable. The increasing release of the greenhouse gasses (GHGs) associated to the onset of the Industrial Revolution (IR) as a beginning of the Anthropocene was later rejected (Certini and Scalenghe, 2011). Instead, the pedosphere was considered as the best recorder of such human-induced modifications of the total environment. Based on the study of the anthropogenic soils (Certini and Scalenghe, 2011), the beginning of the Anthropocene was attributed to ~2000 cal yr BP. After reviewing the onset of the Anthropocene, (Smith et al., 2013) has considered the Anthropocene to be coeval with the Holocene controversially with Waters et al. (2016). This “Anthropocene onset” controversy is mainly due to its regionally depending limits which are not worldwide. Yet, some common features can be found concerning the setting of the Anthropocene: polluted environments and climate change.

In the aftermath of the Anthropocene settings, the term “GA” has emerged as a new concept which documents and describes the increasing impact of human societies on the Earth systems (Steffen et al., 2015). Since 1950, the dramatic increase in most Earth’s systems parameters was attributed to the growing impact of human societies on the ecosystems, and was used to demark the initiation of the Anthropocene (Zalasiewicz et al., 2012) has been later rejected. Regarding this controversy, the Anthropocene Working Group (AWG), a working group of the Subcommission on Quaternary Stratigraphy (SQS) of the International Commission on Stratigraphy (ICS) has been spurring scientists to define the beginning of the Anthropocene in the Geologic Timescale.

The aim of this work is twofold; On the one hand, the content of heavy metal and the magnetic susceptibility measurements were combined to identify the onset of the Anthropocene and the individualization of the GA in Eastern Tunisia in terms of environmental pollution. On the other hand, other geochemical (Ca, Na and K), micropaleontological (ostracods, foraminifera, charophytes and gastropods) and sedimentary (clay, silt and sand percentages) proxies were used to provide further information about the sedimentary dynamic environmental changes related to the Anthropocene settings.

Study area

Geographic location

Coastal regions and estuaries (wetlands) are sensitive environments to record the setting of the Anthropocene (Leorri and Cearreta, 2009; Emeis et al., 2015; Irabien et al., 2015; Waters et al., 2018), unlike mountains which are remote far from the impact of human induced activities (Gabriel and Barbante, 2014). The sebkha-lagoon Halk El Menjel is a 17

km² coastal are located 1 km westward of Hergla harbor (35°58'28"N, 10°31'27"E to 36°00'38"N, 10°27'29"E) (Fig. 1c). It has been considered as a “recipient” of various pollutants (APAL, 2002) notably the heavy metals, resulted of an accelerated industrialization and urbanization of the surrounding vicinities.

Bioclimatic and rainfall setting

In the western part of the Mediterranean Sea (Fig. 1a), Tunisia extends on different climatic stages ranging from: (1) humid to sub-humid zones, (2) semi-arid to arid zones in central Tunisia and (3) arid to saharian zones in southern Tunisia with sub-desert to desert vegetation (Lebreton et al., 2015) (Fig. 1d). Plains and foothills of the study area region are approximately located in the semi-arid bioclimatic zone, between the 200 mm and 400 mm isohyets (Fig. 1d). A long drought summer occurs from March to August, and three aridity gradients are observed: (1) from the sea shore to the Tunisian-Algerian frontier (a longitudinal one), (2) from the North to the South, a (latitudinal one) and (3) along the elevation, an altitudinal one (Lebreton et al., 2015) (Fig. 1). The mean annual temperature is around 19 °C, with mean summer temperature 27.1 °C and mean winter temperature 12 °C (APAL, 2002) while the mean annual rainfall is about 350 mm, ranging from 100 to 680 mm (APAL, 2003). The sebkha-lagoon Halk El Menjel is surrounded by a complex hydrographic network. It collects fresh waters and sediments mainly from sebkha Kalbia through the Menfas and As-sod wadis (APAL, 2002). The sebkha Kalbia itself is fed by hydraulic sedimentation through main wadis of Merguellil, Nebhana and Zroud (Khdheri et al., 2011; Duplay et al., 2013; Kchouk et al., 2015) which incised the southern slope of the Dorsal Mountains (Jbel Trozza, Jbel Serj and Jbel Bargou) (Fincoa et al., 2018; Figs. 1b, c).

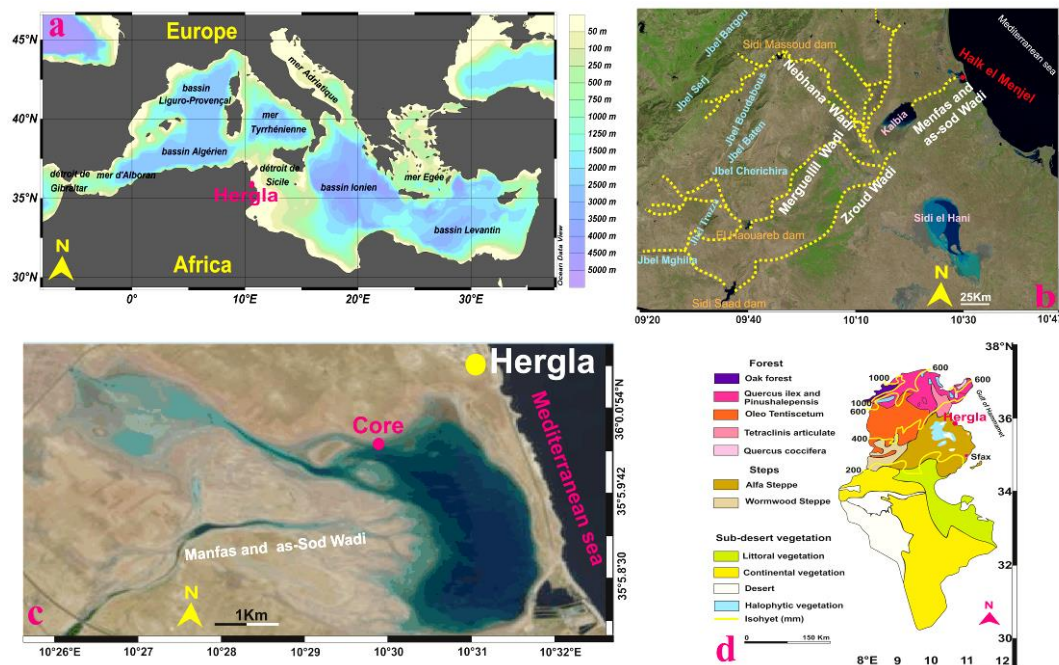


Figure 1. Location of the Halk El Menjel sebkha-lagoon delta system. (a) Connection of Hergla coastal harbour with the Mediterranean Sea. (b) Satellite image (<https://earthexplorer.usgs.gov/>) marked the connection of Halk El Menjel sebkha-lagoon with hydrogeological systems's sebkha endoreic Kalbia. (c) Satellite image (<https://earthexplorer.usgs.gov/>) of sebkha-lagoon Halk el Menjel showing the coring location. (d) Bioclimatic map of Tunisia (modified after Lebreton et al., 2015)

Anthropogenic setting

As for anthropogenic activities, since the Neolithic, the vicinities of the study area have been occupied by primitive to recent human populations (Mulazzani et al., 2010; Belhouchet et al., 2014; Essefi et al., 2014). Moreover, the majority of the coastal areas of Tunisia are threatened by an increasing pollution (Ennouri et al., 2016; Pradel et al., 2016). Also, the climate witnessed an increasing aridity recorded in the micropaleontological (Zaibi, 2011), sedimentary and mineralogical contents (Gargouri, 2011). Connected with the Mediterranean Sea, the wetland of Halk El Menjel is marked by a well-shaped delta system related to a temporary river without a dam (*Fig. 1c*). This type of delta had potentially recorded the variability of sediment flux during the Anthropocene (James and Kettner, 2011).

Methods and materials

Sampling and chronological framework

During the field expedition, a 10-cm long core (HK3) was recovered in the sebkha-lagoon of Halk El Menjel (36°00'01"N, 10°30'08"E) next to the core of (Lebreton et al., 2015), merely few meters of lateral distance. In laboratory, the sediment of the core was sampled each 2 mm to collect 50 samples. Since our core is located exactly next to the core of (Lebreton et al., 2015), we relied on its age-depth model already carried out based on eight dated samples. The mean sediment accumulation rate is ~0.16 mm/yr for the past 3000 yr (*Table 1*), giving, therefore, a total duration of 628 yr for the 10 cm core. Our mean sediment accumulation rate found in sebkha-lagoon of Halk el Menjel is comparable to other sedimentation rates found in different western Mediterranean areas.

Table 1. 14C AMS radiocarbon ages of the studied core (Lebreton et al., 2015)

Laboratory	Lab reference	Depth (m, a.s.l.)	Conventional age (14C yr BP)	Calibrated age (2σ) (calyr BP)	Mean cal age (calyr BP)
Beta Analytic	Beta-290411	-0.58	3410 ± 40	3731–3562	3646 ± 85

Petromagnetic and geochemical analysis

Low and high frequency (LF and HF) magnetic susceptibility (MS) and grain size parameters were measured using Bartington MS2B probe and FRITSCH laser granulometer, respectively. The resulted MS measurements were expressed as mass susceptibility χ_{lf} and χ_{hf} , and the corresponding frequency dependence of magnetic susceptibility (FD) was calculated as follows:

$$FD(\%) = \frac{(\chi_{lf} - \chi_{hf})}{\chi_{lf}} \times 100 \quad (\text{Eq.1})$$

Then, percentages of clay, silt and sand were calculated using/based on the cumulative curves.

Geochemistry is a more relevant tool to assess the Anthropocene environmental changes (Gałuszka et al., 2014). After three concentrated acids (Nitric, perchloric,

chloridric) attack of each sample, the amounts of heavy metals (Cr, Ni, Cu, Zn, and Fe) were measured by atomic adsorption to calculate the geo-accumulation index (Igeo). Igeo is considered as a relevant criterion to determine the degree of sediments metal contamination by comparing current concentrations with pre-industrial levels (Müller, 1981). It can be calculated using the following equation:

$$I_{geo} = \log_2 \left[\frac{C_n}{1.5 \times C_{Bn}} \right] \quad (\text{Eq.2})$$

where C_n is the measured concentration of the examined metal (n) in the sediment, B_n is the background concentration of the metal (n), and 1.5 is the background matrix correction factor due to lithogenic effect. According to the scale of (Müller, 1981), the calculated Igeo related to the studied samples showed different levels of contamination for the analyzed metals (Table 2).

Table 2. Sediment classes according to Müller (1981)

Geo Index value	Class	Quality of sediment
Less than 0	0	Unpolluted
0-1	1	From unpolluted to moderately polluted
1-2	2	Moderately polluted
2-3	3	From moderately to strongly polluted
3-4	4	Strongly polluted
4-5	5	From strongly to extremely polluted
More than 5	6	Extremely polluted

In addition, Ca^{++} , K^+ , and Na^+ contents were measured, following two methods: attacked and bulk sediment. These analyses were carried out using Flame Photometer in Geochemistry Laboratory in the National Engineering School of Sfax (Tunisia). In saline systems, the measurement of Ca^{++} , K^+ , and Na^+ by the acids attacked, includes both those due to past climatic change and those due to present groundwater feeding, whereas measurement on bulk shows the cations related to groundwater feeding. Hence, the subtraction result highlights the climatic signal (Essefi et al., 2015) recorded in the studied wetland.

Paleobiological analysis

The fauna within samples was studied to find out the defaunation at the onset of the Anthropocene. Each sample was disaggregated with diluted hydrogen peroxide for 4 to 5 h and washed into 250 μm and 63 μm sieves. The residues were dried under 50 °C then the density of foraminifera, ostracods, charophytes and gastropods was calculated (in individual/kg).

Principal component analysis (PCA)

To understand the relationship between various parameters related to the Anthropocene and GA, or other possible sources of production, the Principal

Component Analysis (PCA) of the, χ_{lf} , χ_{hf} , FD, heavy metals (Fe, Zn, Cu, Cr, and Ni contents), clay, silt and sand percentages was computed and plotted on the PCA diagram.

Results

The 10 cm of the studied core HK3 represents the fifth pollen zone PZ-5 (Fig. 2) at the top of the core of (Lebreton et al., 2015) reflecting the modern local and regional semi-arid vegetation. At the middle of this biofacies, an abrupt appearance of the Oleaster wild olive species (*Olea europaea* subsp. *Europaea* var. *sylvestris*) can be noticed (Lebreton et al., 2015). It is worth noting that the Oleaster is relevant to the Mediterranean regions and belongs to the thermophilous Mediterranean vegetation, indicating arid conditions probably related to the setting of the Anthropocene. The latter age and the subsequent GA might be also recorded through chemical (heavy metals), sedimentological (clay, silt, and sand percentages), and paleontological (foraminifera, ostracods, charophytes, gastropods) proxies.

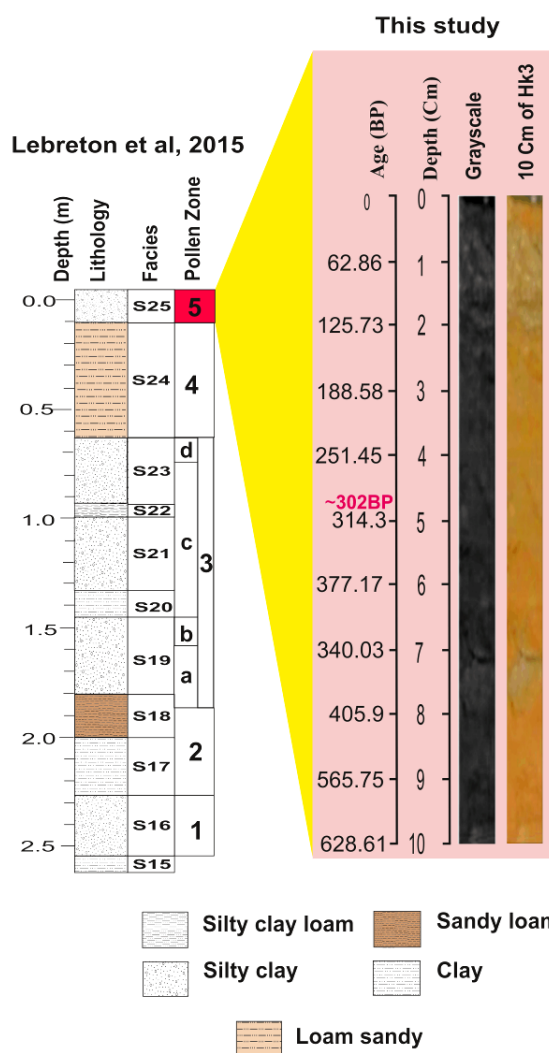


Figure 2. Relationship between Lebreton core and the 10 Cm of HK3 core from the sebkhalagoon of Halk El Menjel

Heavy metals content during the Anthropocene-Holocene transition and the Great Acceleration

The evolution of the heavy metals content (Fig. 3) shows an upward increasing pollution related to the setting of the Anthropocene. According to the age-depth model (Fig. 2), the polluted period may have started at ~300 yr BP, and henceforth, all heavy metals contents have increased indicating an important source of pollution. Worldwide, the Anthropocene is marked by a dramatic increase of heavy metals content in the exceptionally damaged wetlands due to natural and/or anthropogenic origins (Álvarez-Vázquez et al., 2016). In fact, multiphase heavy metals geochemical processes interfere in the atmosphere-biosphere interface, influencing the climatic conditions during the Anthropocene (Pöschl and Shiraiwa, 2015). Nonetheless, due to their natural and anthropic origins, absolute values of heavy metals contents relevant to the Anthropocene still are ambiguous and cannot serve as a pacemaker for the setting of its limits. In the case of the Halk El Menjel wetland/sebkha-lagoon, this proxy may only show the existence of an increasing pollution. To get over this limitation, we need to compute the Igeo to determine the degree of contamination. Moreover, the increasing trend of some heavy metals contents such as Zn is more pronounced at the top of the core due to their anthropogenic impact during the GA. However, heavy metals having natural origin such as iron do not show an obvious increase. Cr, Cu and Ni indicate a rapid setting rate of the Anthropocene dating back to ~300 yr. The content of all heavy metals does not show an obvious individualization of the GA.

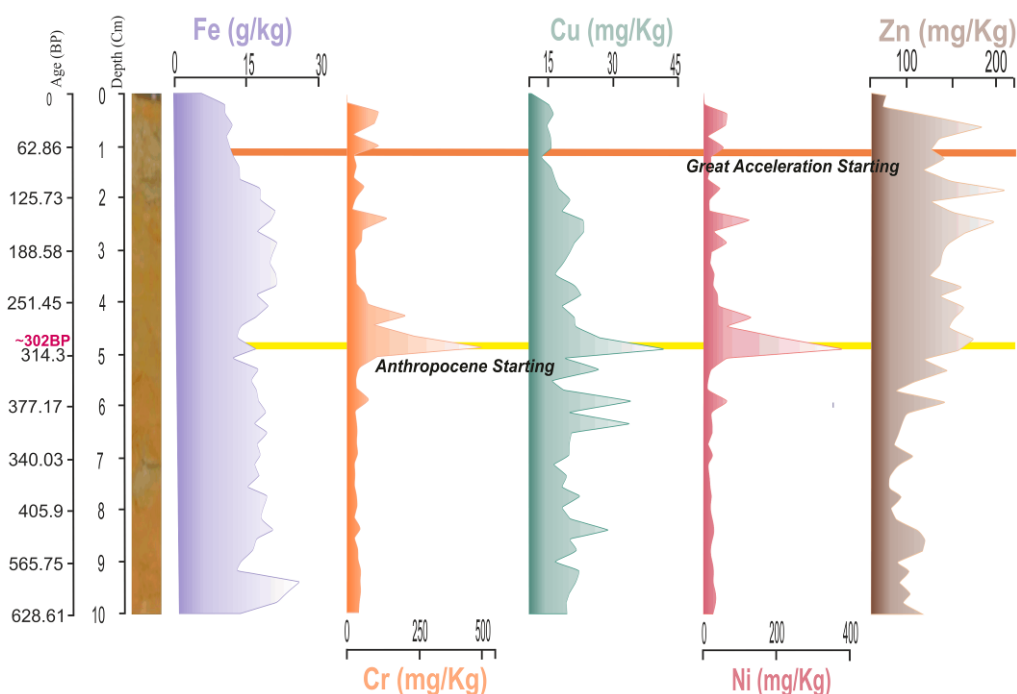


Figure 3. Evolution of the heavy metals content along the 10 cm core from the sebkha of Halk El Menjel

Due to the overlap of the natural and anthropogenic factors in wetlands, the onset the Anthropocene and the GA based on heavy metals is not straightforward. This led us to calculate and plot the Igeo against the core (Fig. 4), which enhanced more the

visualization of the Anthropocene limit already identified through the bulk content of heavy metals. In fact, the study had experienced the succession of many civilizations who had used fire and old traditional tools (Lebreton et al., 2015). The Igeo of Zn, Cr, Ni and Cu along the core may also points to the setting of Anthropocene at ~300 yr PB, whereas the GA is well pronounced through the Igeo of Ni and Cr. The Igeo varies from strong to extreme polluted for Cr and Ni and is moderately polluted for Zn, Cu and Fe, which allowed us inferring that the sebkha sediments are contaminated by heavy metals the same way as many Tunisian coastal regions (Gargouri, 2001; Ghannem et al., 2011, 2014; Wali et al., 2015).

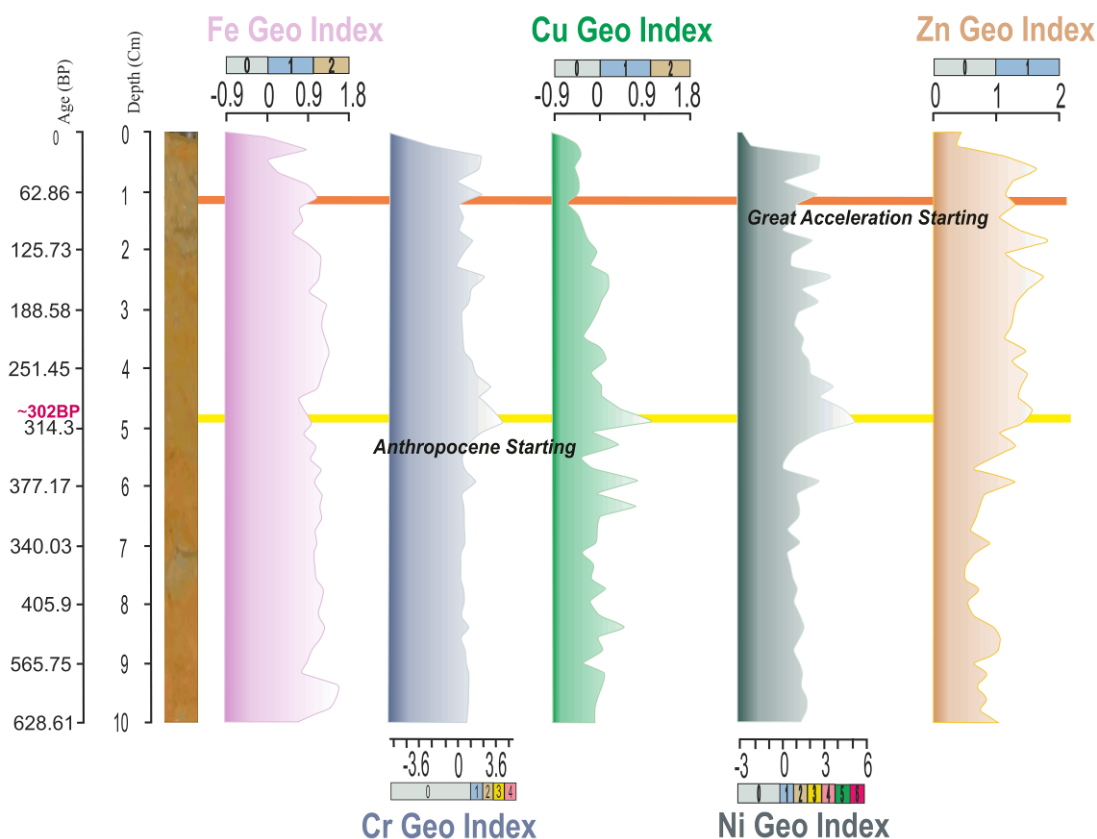


Figure 4. Evolution of Geo-accumulation Index along the 10 cm core from the sebkha of Halk El Menjel

Grain size variability during the Great Acceleration and the Anthropocene-Holocene transition: the sedimentary flux

The variability of clay, silt and sand percentages (Fig. 5) is related to sedimentary flux which has increased considerably indicating a dramatic climate change particularly during the GA (James and Kettner, 2011). Actually, scientists (Ribot, 2014) are still debating concerning the realistic scenarios of the climate change during the Anthropocene because of the overlap of the natural and the anthropogenic causes. Grain size parameters (Fig. 5) show an upward tendency toward a decrease of clay percentage unlike silt and sand percentages which increase considerably along the last 5 cm of the core HK3. This may indicate an increase of the hydraulic sediment flux, which is

related to some human induced activities worldwide taking place during the Anthropocene and GA (James and Kettner, 2011): (1) soil erosion related to deforestation, slope failure and downstream sedimentation; (2) agricultural activities in the Eastern Tunisian coastal region consist of tillage, irrigation systems, terracing, and subsurface water pumping, leading, respectively, to an increased soil erosion, creep, siltation and subsidence. The coastal management takes place along the wetland shoreline through groynes, jetties, seawalls, breakwaters and harbours, causing unnatural coastal erosion or sedimentation, as well as wetland, mangrove and dune alterations; (3) the waterway construction, including reservoirs and dams, diversions, channel levees, discharge focusing, channel deepening and ultimately coastline erosion.

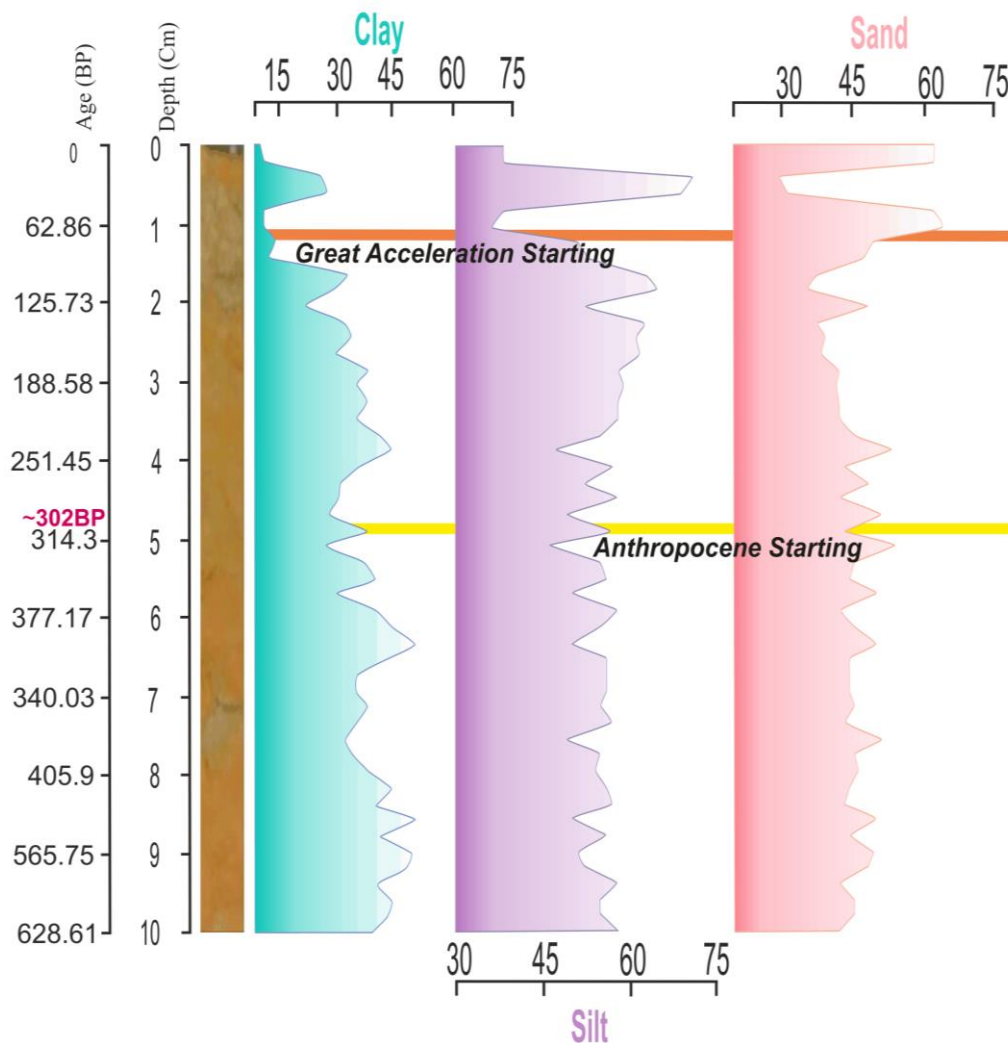


Figure 5. Evolution of grain size parameters along the 10 cm core from the sebkha-lagoon of Halk El Menjel indicating an increasing sediment flux

Geochemical proxies' evolution during the Great Acceleration and the Anthropocene-Holocene transition

Climate conditions and sea-level change may have a direct impact on the geochemistry of the sedimentary record. These changes deal also with aeolian erosion

and perturbation of the surface geochemistry characteristics during the Anthropocene (Marx et al., 2014). Toward the inland, Anthropocene conditions change the response of the main Wadis feeding the studied sebkha (Meybeck, 2001; James and Kettner, 2011). The increase of Ca^{++} , Na^{++} and K^{+} contents is a direct indicator of an increasing aridity and/or sea level fall. The vertical evolution of these ions contents (*Fig. 6*) does not indicate a systematic variability relevant to the Anthropocene settings. Compared to other stratigraphic changes described in longer geologic periods, the climate and sea-level signals of the Anthropocene are not strongly expressed, because they reflect, somehow, the combined effects of fast and slow climate feedback mechanisms.

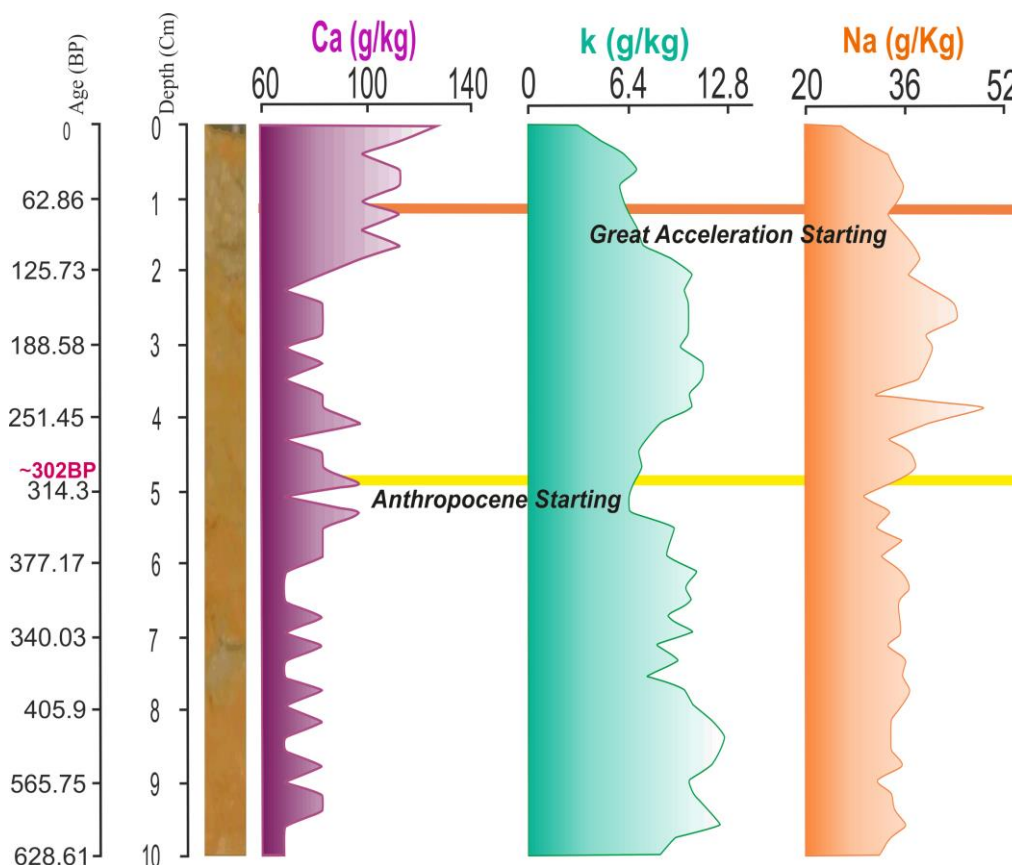


Figure 6. Evolution of Ca, Na and K contents along the 10 cm core from the sebkha of Halk El Menjel

Magnetic susceptibility evolution during the Great Acceleration and the Anthropocene-Holocene transition

The convolution of the geochemical data of attacked and non-attacked sediments plotted against the magnetic susceptibility (*Fig. 7*) does not match well the setting of the Anthropocene. Instead, its cyclic pattern may be related to astronomic and/or oceanographic forcing. The magnetic susceptibility variations may go in line with the heavy metals content (Dearing et al., 1996, 2001). Also, the setting of a new microbiologic response related to the Anthropocene may be the origin of the development of magnetobacteria (Gillings and Paulsen, 2014), which are responsible for the increasing pattern of the magnetic susceptibility variations. The use of

petromagnetic measurements in wetland sediments as a marker for the start of the Anthropocene has been widely adopted recently. Indeed, the starting of the Anthropocene is worldwide marked by an increase of the magnetic susceptibility in recent sediments (Olfield, 2001).

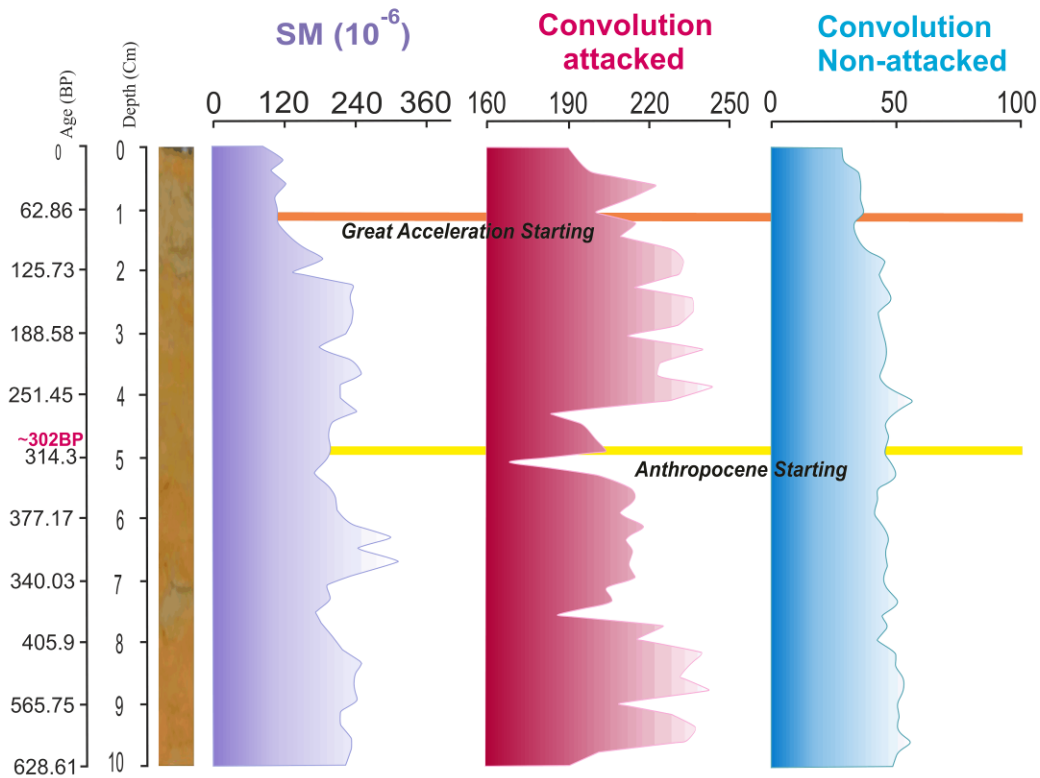


Figure 7. Evolution of the magnetic susceptibility and the convolution of geochemical elements (Ca, Na, K) for the attacked and non-attacked sediment along the 10 cm core from the sebkha of Halk El Menjel

Principal Component Analysis: an overview on the behavior of the proxies and these agents of control during the Anthropocene-Holocene transition

The Principal Component Analysis PCA of all variables (Fig. 8) shows the individualization of three different groups. The first one is made up of χ_{lf} , χ_{hf} , Clay percentage and Iron related to wetter climatic conditions and/or sea level fall which triggered a sediment flux during Anthropocene. The second group is made up of the heavy metals Cu, Cr, Zn and Ni. As it is indicated by the Igeo values, it is related to an environmental pollution. During the Anthropocene, heavy metals pollution had been caused by natural and anthropogenic factors. Although that various anthropogenic sources contribute to heavy metals pollution in the environment, the most important source remains the mining activities that lead to a global dispersal through oceanic and atmospheric dissemination. The third group is made up of FD, silt and sand percentages. It is related to sea level rise and/or and increasing erodability. The PCA shows the overlap of natural and human induced effects during the Anthropocene. The pollution and climate change combined together had generated the Anthropocene conditions.

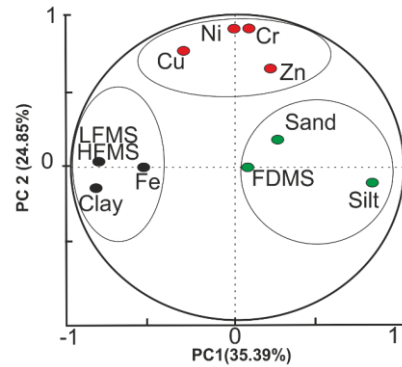


Figure 8. Principal Component Analysis of geophysical (LFMS, HFMS and FDMS), geochemical (Fe, Zn, Cu, Cr, and Ni contents) and sedimentological proxies (clay, silt and sand percentages)

Defaunation during the Anthropocene

One of the most interesting targets of the Anthropocene definition is the search for a wider understanding of how human activities have modified and disturbed the Earth's ecosystems and biological resources. In terms of paleontological content, marine foraminifera show an obvious defaunation due to the setting of stressful conditions related to coastal pollution starting since the Anthropocene onset and accentuated during the GA. The defaunation of continental charophytes is probably due to the synergetic effects between human activities eutrophication and climatic conditions disrupting their intensity of the population density (Fig. 9). Ostracods are not obviously influenced during the Anthropocene and began to increase dramatically during the GA. Likewise, gastropods remain not obviously influenced during both periods. The anthropic acceleration of fauna and flora extinctions during the Anthropocene and the GA due to pollution or climate change have been noticed for many species (Braje and Erlandson, 2013). In fact, anthropogenic climate change is playing an important role; the primary operator of modern extinctions seems to be habitat loss, introduced species and human predation (Briggs, 2011).

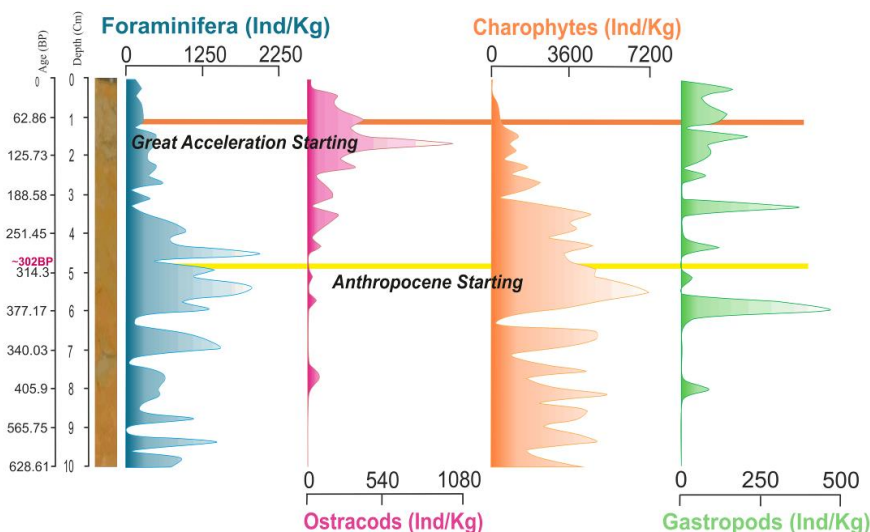


Figure 9. Evolution of fauna density (individuals per kg) along the 10 cm core from the sebkha of Halk El Menjel

Discussion

Early to middle Little Ice Age (LIA) (AD 1400- 1712)

In this work, we consider this interval as a pre-Anthropocene period. It is marked by a lower fluctuation of pollutants; weak rate of Cr and Ni and moderate rate in Cu and Zn (Figs. 3, 4 and 10). This fluctuation may be related to atmospheric metal deposition which have had a causal link to a natural source due to two major volcanic eruptions of Kuwae (Vanuatu, Southern Pacific) and St. Helens at AD 1452-1453 and 1480-1482 respectively (Yamaguchi, 1983; Gao, 2006). For example, the particular Kuwae volcano emitted to the atmosphere some of the broadest aerosol fluxes in the past 700 years (Buat-Menard and Arnold, 1978). Indeed, many heavy metals have been found at an increased concentration in volcanic emissions; metals (Fe, Cr, Cu, Mn, Ni, Pb, and Zn among others) and polluted gases (CO₂, sulfur and chlorine compounds) (Buat-Menard and Arnold, 1978; Favalli et al., 2004; Andronico et al., 2009). In addition, the volcanic eruptions during this period are the major natural source of many heavy metals such as gaseous mercury (Hg) emissions to the atmosphere which may include more than 1000 mg of Hg per event (Nriagu, 1990; Nriagu and Becker, 2003; Pyle and Mather, 2003), 40-50% of the global flux of Cd (Nriagu, 1990; Pyle and Mather, 2003), and 20-40% of other volatile metals (As, Cu, Ni, Pb and Sb) (Nriagu, 1990).

Mediterranean basin was marked by the development of mining activities during the early LIA (Corella et al., 2017) especially, in Spain (Rio Tinto mining, Mines of Parzán and Almadén mining) and Slovenia (Idrija mine) (Corella et al., 2017). Nevertheless, anthropogenic emissions have greatly overpassed natural release to the atmosphere over historical times (Allan et al., 2013; Beal et al., 2015; Corella et al., 2017; Erykh et al., 2017). Most of heavy metal contents show a slight (Fe and Cr) to significant (Ni and Zn) increase after the Anthropocene onset (Fig. 4) which could be explain by the double impact of natural and anthropogenic pollution sources.

This period represented the early to middle LIA which this last framed within the Medieval Climatic Anomaly (MCA) and post-LIA warming recorded during the second half of 19th century. LIA is a one of the coldest periods over the Northern Hemisphere during the Holocene (Grove, 2004; Wanner et al., 2011), it was characterized by cold periods with regionally variable magnitude controlling by a various mechanisms associated to external forcing mechanisms (Hunt, 2006) where the main processes was attributed to the increasing volcanic activity (Crowley, 2000; Hegerl et al., 2011) and radiative forcing (Solar Irradiation) (Dorado-Liñán et al., 2016) represented by two major grand solar activity minima; the Spörer minimum (1460-1550) and the Maunder minimum (MM) (1645-1715) (Eddy, 1976). This external forcing, especially volcanic aerosols have been initiated to multidecadal changes in internal climate system mechanism (ocean heat content (OHC), Arctic sea ice extent, the Atlantic Meridional Overturning Circulation (AMOC), and Sea Surface Temperatures (SSTs)) through a series of climate feedbacks. (Broecker, 2000; Church et al., 2005; Hegerl et al., 2011; Iwi et al., 2012; Schleussner and Feulner, 2013; McGregor et al., 2015). The multi-decadal timescales mechanisms caused a succession of warm and cold 'sub-periods' with an irregular annual and seasonal precipitation bring about to both floods and droughts (Machado et al., 2011). This climate fluctuation may explain the particular trend of our measured data in *Figure 5* (%sand, %silt and %clay). In fact, the grain size parameter measured along the HK3 core show a particular pattern which goes in line with the pre- and the post-climate setting of the Anthropocene. The latter, which is

characterized by long negative NAO phases (Baker et al., 2015) (*Fig. 10.13*) leading to wetter conditions (Benito et al., 2003, 2015) and more pronounced flooding events, shows higher coarse fractions (silt and sand) (*Fig. 5*) during the early to middle LIA comparing to finer particles (clay) which decrease obviously after the proposed Anthropocene onset (*Fig. 5*).

Late LIA: the Anthropocene onset (AD 1712-1850)

This transition is marked by a dramatic increase of heavy metal contents (*Fig. 3*) and Igeo values (particularly the Ni and Cr) (*Figs. 4, 10.1, 10.2, 10.3 and 10.4*) increasing records which can be attributed to natural and anthropogenic sources. Firstly, the natural one is related to volcanic eruptions which are frequent in Mediterranean Sea; series of explosive volcanic eruptions causes an increase in the levels of atmospheric metals such as (1) Vesuvius explosive eruption (Italy, Tyrrhenian Sea) in AD 1631 (Barberi et al., 1995), (2) the most violent phase of explosive eruption of Kolumbo (Greece, Aegean Sea) marked at AD 1650 (Fouqué, 1879; Ulvrova et al., 2016), (3) AD 1669 represented the largest historic eruption during the last 400 years of Etna (Eastern Sicily, Ionian Sea) (Tanguy et al., 2007; Branca et al., 2013) and (4) Santorini volcanic eruption from AD 1707-1711 (Greece, Aegean Sea) (Gorée, 1710; Tarillon, 1715; Watts et al., 2015). Aerosols injected into the atmosphere during explosive eruptions consist of mixtures of varying particles such as gases, soot, ash, secondary organic aerosols, metals and mineral dust (Pyle and Mather, 2003; Seinfeld et al., 2006). Aerosols can be transported by turbulent mixing and convection atmospheric circulations to remote higher altitudes or other continents before they are eliminated from the atmosphere by dry and/or wet deposition. Secondly, the mining activity is considered as the most important source of the anthropogenic emissions and pollution before the Industrial Period (IP) in Western Mediterranean region (Cortizas et al., 1999, 2002; Allan et al., 2013). It has largely overpassed the natural sources of pollution since the Anthropocene onset henceforth. Southern Spain is known as a historical mining area; the Almadén mining district (since 2500 yr BP) (Cortizas et al., 1999) and the Bielsa-Parzán mining district (since pre-Roman times) (Calvo, 2008). Moreover, the border of the 'Massif Central' (Southern France) has been known as an important mining area of non-ferrous (Pb-Zn-Ag-Au) metals since at least the medieval period (Poulichette et al., 2017). Consequently, a growth stock of metal deposit (Kaye, 2005; Poulichette et al., 2017) is concentrated in the mining areas which represented a potential environmental risk in the Mediterranean basin during contemporaneous storms and flooding events (Salomons and Förstner, 1984; Blais et al., 2015).

The accumulation of pollutants coincided with transition period under particular climatic conditions marked by the transit from the MM period to relatively higher δ TSI (Herrera et al., 2015) (transit phase from a very cold period to warmer period) (*Fig. 10.16*). This change in TSI had controlled the contemporaneous NAO pattern (*Fig. 10.13*), which is in turn, controlled the main climate variability in the Mediterranean region during the last 500 years (Luterbacher et al., 2002; Hurrell et al., 2003). Negative NAO phase triggered the precipitation and the river runoff which caused frequent floods in the Western and Central Mediterranean region (Benito et al., 2015). When the NAO is positive, dry conditions develop over North Africa and southern Europe (Nieto-Moreno et al., 2015).

Moreover, Dezileau et al. (2011) have reported that the late LIA was a period of superstorm activity in the Western Mediterranean region with high fluvial activity and

major historical flooding events which might lead to an increasing detrital flux into the Mediterranean basin and high sand level which has been shown by our data (*Figs. 5 and 10.7*). Several authors have documented a major periods of high flood frequency occurring in Western Mediterranean region during the late 17th and beginning of 18th century; (Degeai et al., 2017) shows a flood event in Southern French coastal region between 1660 and 1780, (Barriendos and Fernando, 2006) described Large Catastrophic Events in northeastern Spain during 1651 (Segura River basins), 1663 and 1678 (Coastal basins of Catalonia). These extreme climatic conditions coincided with progressive increase in atmospheric pollutants and huge quantities of hazardous mine wastes from polymetallic ores for the production of Pb, Zn, Ag, As, Hg, Ti, Sb, Cd, Au, Cu... (have been heavily worked in Mediterranean regions since pre-Roman times) due to mining processing and smelting activities which had been transported to the Mediterranean basin (Poulichette et al., 2017). Spanish and French rivers discharging to Mediterranean basin are able to transport mining contaminants, during the flooding events and remote from their sources (Puig et al., 1999; Baudrimonta et al., 2005; Poulichette et al., 2017) even though the mines are abandoned (Pyatt et al., 2000; Audry et al., 2004; Baron et al., 2005, 2006). Spanish rivers play a very important role through its evacuation point which is the Alboran Sea. In terms of oceanography, the Alboran Sea is considered as master piece of the thermohaline circulation; it is the place of mixture by Alboran Gyre of the incoming Atlantic waters (AW) through Gibraltar Strait (Jordà et al., 2017; Testor et al., 2018) with the previously mentioned polluted water of main Spanish rivers. AW are rapidly becoming Modified Atlantic Waters (MAW) (La Violette, 1987; Tintore et al., 1988; Arnone et al., 1990) and progress eastward up to Eastern Mediterranean. Most of French rivers (The Herault river basin and The Gardon river basin which is the tributary of the Rhone River) evacuated polluted waters in the Gulf of Lion (GoL). This leads to consider that no water mass in the Mediterranean Sea can escape the anthropogenic metal inputs including the Tunisian coastal regions, and hence, our study area of Sebkh-lagoon of Halk El Menjel. Therefore, the origin of the second group shown by the PCA (Cu, Cr, Zn and Ni) (*Fig. 8*) may be linked to this kind of transport and their Igeo values to these sources of contamination (*Figs. 4, 10.1, 10.2, 10.3 and 10.4*).

At the end of 17th century and the dawn of the 18th century, the synergetic effects between human activities and climate change in Tunisian regions were particularly intense and have been accentuated further with demographic development in coastal areas and around the rivers' vicinities (Ghazali, 2003; Chaldeos, 2016; Cherni et al., 2016). This situation, associated with human-induced soil erosion (Lacarra, 1972), had led to the so-called anthropogenic land cover change (ALCC). This had been spurred further by the use of fire for the creation of pastureland and cropland, and the use of coal in factories which was significantly intensified (Houghton et al., 1996; Ruddiman, 2007) at the end of the 18th century. Our dataset (grain size parameters) support this fact as we notice a remarkable increase of % clay, % silt and % sand during this period (*Fig. 5*). The increasing of population affecting the environment (Smith and Zeder, 2013) particularly the marine ecosystems caused an eutrophication (Lotze et al., 2011) which was triggered by a huge discharge of suspended matter, nutrients and trace elements (Degobbis et al., 2000; Zonneveld et al., 2012; Salvi et al., 2015). Consequently, a defaunation occurred marked by a noticeable falling in the intensity of the population density of marine organisms (including foraminifera, gastropods and ostracods) (*Figs. 9, 10.10, 10.11, and 10.12*). However, increasing heavy metals seems

to be affectless on charophytes population density; no significant influence of Cu, Co and Ni has been evidenced on charophytes occurrence (*Figs. 10.2, 10.3, and 10.9*) (Lamber and Davy, 2010) on their population density. Yet, a slight decrease is noticed around the Anthropocene onset. Actually, charophytes are known as a sensitive indicator of water clarity. The occurrence of most charophytes is limited to clear water columns with alkaline pH and low nutrient amount (Phillips et al., 2005) which seems to be perturbed by increasing detrital inputs triggered by major flooding events during this period.

Industrial period

This period is known as the first acceleration phase during which anthropogenic heavy metal environmental pollution begun with mining activities, the domestication of fire and later the Industrial Revolution (IR). The IR yielded a higher demand for metals, excessive burning of fossil fuels and an exponential increase in the intensity of heavy metal pollution (Nriagu, 1996). Consequently, an increasing level of aerosol particles in the atmosphere as well as the increase in GHGs caused an unprecedented sunlight reflection, and triggered, thus, the global warming (Owens et al., 2017). As a result, a potential contamination might be globally widespread into the environment (air, water, soils, sediments) including Tunisian coastal zones. Our data show an important Igeo value for Cr, Ni and Zn (*Figs. 4, 10.1, 10.3 and 10.4*) which may represent the aftermath of this contamination. The industrialization was associated with a decrease of average ocean surface waters pH by ~0.1 (induced by deposition of acidifying pollutants or microbial oxidation of sulphides and ammonia to form sulphuric and nitric acids (Feely et al., 2009; Rice and Herman, 2012)) and an abrupt increase in CH₄ presumably caused by increased fossil fuel emissions (Houweling et al., 2008; Mischler et al., 2009; Sapart et al., 2012). The combination of both the environmental acidification phenomena (Rice and Herman, 2012) and the eutrophication had yielded the damage of marine communities and had reduced species diversity (de Faveri et al., 2015); foraminifera (industrial period is characterized by an increase of warm water species (Margaritelli et al., 2016)) and charophytes which are known as sensitive indicators of indirect consequences of eutrophication (water quality, lack of light, water clarity and sediment accumulation (Phillips et al., 2005)). Some other species can also show a tolerant response to anthropogenic stress (Suárez-Álvarez et al., 2012; Sarker et al., 2013), such as gastropods and ostracods were found predominantly during the following the IR which dose match very well our fauna data in *Figure 9*.

Modern Warming Period (MWP)

This period started with the so-called “GA” in 1950. The GA marked the transition between the IP and the Modern Warming Period (MWP) which is characterized by globally-widespread anthropogenic impact on planet Earth (McNeill, 2000; Steffen et al., 2004). The abrupt increasing in human activities resulting from the rising of world population density (*Fig. 10.9*) from 3 to 6 billion in only 50 years (Steffen et al., 2011) is the main cause of global warming (IPCC, 2007). The level of CO₂ emissions had risen sharply to 379 ppm according to the 2005 measurements (Altava-Ortiz et al., 2011). This increase has been caused by the burning of fossil fuels and the changes in land use which make up the largest share of the GHG emissions. Furthermore, other non-CO₂ greenhouse gases such as nitrous oxide (N₂O) and methane (CH₄) also

contribute substantially to the overall warming GHG. Atmospheric CH₄ had increased from ~900 ppb in 1900 to ~1800 ppb in 2010 (Ghosh et al., 2015). The combined effect of these factors with the Total Solar Irradiance (TSI) (*Fig. 10.16*) caused an increase in the Sea Surface Temperature (SST) since the 1950s. This increase of the SST has affected the global rainfall (Bozkurt and Sen, 2011) particularly in the Mediterranean basin (Turuncoglu, 2015) which caused an important ingredient for the onset and the intensification of Heavy Precipitation Events (HPE), especially in its western part (Miglietta et al., 2011; Pastor et al., 2015, 2018), Central Europe (Volosciuk et al., 2016) and the coastal regions of Tunisia (Rowell, 2003). Moreover, Marcos et al. (2009) noticed a significant correlation between the storm events in the Western and Central Mediterranean and the NAO pattern.

Two peaks are obviously distinguished in the heavy metals Igeo during the second half of the 20th century which might be correlated to the Western Mediterranean HPE (WMHPE) especially Tunisian flooding events (*Figs. 10.1, 10.2, 10.3, and 10.4*). The first peak coincides with positive NAO phase (*Fig. 10.13*). Yet, HPE was documented over Western Mediterranean basin during the 1960s (Valencia flooding on October 1957 in Barcelona in September 1962 (Olcina et al., 2016)) which may be due to positive AMO phase (Gray et al., 2004) (*Fig. 10.14*). Tunisia was affected by an exceptional flooding event in 1969 with a return period estimated at 150 years (Besbes et al., 2019). The Oued Zeroud flooding on 27 September 1969, had a maximum flow of 17,000 m³/s, seven times higher than the historic flooding of 1910 in Paris (2400 m³/s) with a five-times smaller watershed (Besbes et al., 2019) and the Merguellil wadi flow exceeded 3000 m³/s (grain size parameters). A second peak occurred during the 1980s, coinciding with an increase in the global SST (IPCC, 2013) and the transition to a positive NAO (Pastor et al., 2018) phase (*Fig. 10.13*). Yet, some floods episodes occurring since 1980 in the Western Mediterranean (Olcina, 2009; Cortesi et al., 2012). That decade began with possibly the flooding of 1982; October's flooding in Valencia, November's flooding in Andorra and the Catalan Pyrenees and the flooding of August 1983 in the Basque Country (1982-1990) (Olcina, 2009). Likewise, Tunisia experienced such remarkable flooding events during the same period (Ellouze and Abida, 2008; Daoud, 2013; Fehri et al., 2014) which goes in line with our Igeo dataset in *Figures 10.1, 10.2, 10.3 and 10.4*. During flooding events, the capability of a fluvial system to lift and carry on detrital influx (*Figs. 10.7, and 10.8*), including heavy metals, far from their origin increases significantly which is the case for Zeroud, Merguellil and Nebhana wadis (Hollis and Kallel, 1986) (*Fig. 1b*). The Zeroud wadi incised the surrounding catchments of the Jebel Trozza ancient mine (active between 1907 and 1937) which is considered as an important pollution source (Duplay et al., 2013; Elmayel et al., 2019). A third remarkable peak occurred during the dawn of 21st century but concerns only the %sand. It may be related to the flooding events that affected North Africa during this period. Indeed, the decade began with the catastrophic flash floods that affected Algeria (10 November 2001) (Tripoli et al., 2005) and Tunisia (2003) (Kadomura, 2005). Nevertheless, heavy metal contents show a very low response to such events which may be related to the construction of the Sidi Saâd dam (1982) (Bel Hadj Salem et al., 2012) and the Houareb dam (1989) (Leduc et al., 2009) upon the Zeroud wadi and Merguellil wadi respectively. These wadis surround the ancient mine of Jebel Trozza and are responsible for the main transport of heavy metal pollution in this area. Consequently, the hydraulic exchange between the Kalbia and Halk El Menjel wetlands (*Fig. 1b*) had been reduced dramatically and affected the heavy metal pollution in the study area.

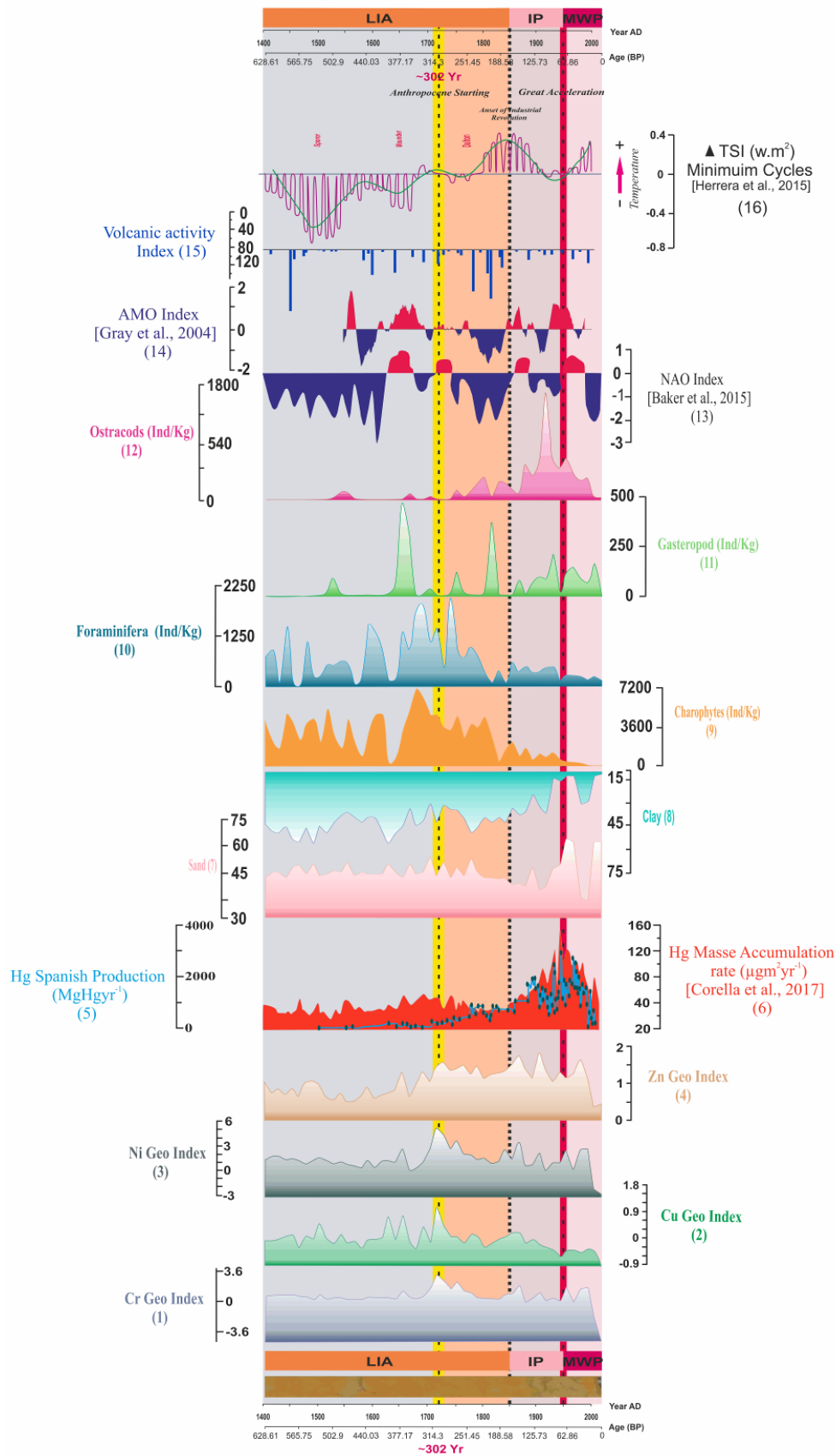


Figure 10. Synergy of anthropogenic, natural and climatic factors to understand Anthropocene phenomena and the Great Acceleration

Continued global warming, in combination with other human-caused stresses and anthropogenic factors would have important consequences for the changing in physical, biological, and chemical processes in soils and water (McNeill and Engelke, 2016). The expected increasing of atmospheric CO₂ cause a reduce of oceanic pH and carbonate ion concentrations (Bates et al., 2008; Waldbusser and Salisbury, 2013): the current pH of the surface ocean of about 8.1 (Feely et al., 2009) has already decreased by 0.1 units since the end of the pre-industrial period (Solomon et al., 2007; Gattuso and Lavigne, 2009) and the acidity of the ocean surface has increased by 30% (Dupont and Pörtner, 2013). Coastal areas were the most sensitive regions where the acidification and the warming of the sea water columns can interact synergistically in decreasing the calcification (Bates et al., 2008) which caused a weakening population density for many calcifying marine organisms (Fabry et al., 2008) such as charophytes (*Fig. 10.9*) cold-water corals, coralline algae, sea urchins and plankton (Reynaud et al., 2003; Anthony et al., 2011; Andersson and Mackenzie, 2011; Kroeker et al., 2013). Besides, the density of foraminifera community had been affected by oceanic acidification which shown an abundance fall (Hall-Spencer et al., 2008; Martin et al., 2008) (*Fig. 10.10*), and also shifts from one majority dominated by calcareous forms to one minority dominated by agglutinated taxa (Hall-Spencer et al., 2008; Dias et al., 2010; Pettit et al., 2015).

Gazeau et al. (2013) have reported that the decrease of pH below 0.4 unit compared to the current value seems to be without any effect on gastropods due to their ability to regulate their internal acid-base equilibrium, shell mineralogy and also their environmental conditions which explain their resistance to intolerant conditions. However, our dataset (*Fig. 10.11*) shows that gastropods density decreased during the MWP. This could be explained by the decrease of influx of dissolved oxygen (DO₂). The latter parameter depends on the input of organic matter and nutrient (Diaz and Rosenberg, 2008; Levin et al., 2009) from coastal watersheds during wet period which causes the increase of the biological oxygen demand by aerobic microbial communities. This environmental change seems to be the major factors influencing the densities of many species such as gastropods and ostracods (*Figs. 10.11 and 10.12*), (Levin and Gage, 1998; Rabalais et al., 2010).

Conclusion

This work implements a multidisciplinary approach to set the limit of the Anthropocene and the subsequent GA in eastern Tunisia. Based on previous published age-depth model and analyses of heavy metals (Cu, Cr, Ni, and Zn), the Anthropocene-Holocene boundary is likely located at 300 yr BP. At this age, the Igeo indices increased significantly indicating hence more pronounced polluting activities. Igeo (particularly the Ni and Cr) shows also several positive peaks indicating, thus, remarkable polluting activities since the GA and hence forward. In term of sedimentologic features, the onset of the Anthropocene is marked by an increasing sedimentary flux indicated by the dominance of the coarse fraction comparing to finer sediments. In addition, the marine fauna was affected by a sharp defaunation during the Anthropocene period related to the setting of stressful environmental conditions. The eutrophication of the sebkha-lagoon Halk El Menjel had been triggered by a huge discharge of suspended matter, nutrients and trace elements during flooding events which caused a falling in the intensity of the population density of marine organisms (including foraminifera, gastropods and ostracods and charophytes). During the MWP, the acidification and the warming of the

sea water columns caused a weakening calcification phenomenon and decrease in population density for many calcifying marine organisms such as charophytes. The decrease of the gastropods and ostracods density seems to be affected by the decrease of the dissolved oxygen (DO₂) during remarkable flooding events.

The Principal Component Analysis found out three groups; two of them are related to natural change of environmental conditions. One group is related to the impact of polluting activities. The human induced activities on the natural environments have dual effect: pollution and climate change.

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