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Correlation between pollution and decline of Scleractinian *Cladocora caespitosa* (Linnaeus, 1758) in the Gulf of Gabes

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Abstract

During an expedition in 2014 in the Gulf of Gabes that aimed to evaluate the impact of the pollution of the phosphate industry on the marine environment, numerous dead coral fragments were retrieved from several stations along a 18 km long transect in front of the industry complex of Gabes. Detailed taxonomy of these coral fragments shows clearly that all fragments belong to the species *Cladocora caespitosa* (Linnaeus, 1758). Quantitative analysis of the coral fragments indicates a positive correlation with stations characterized by positive bathymetric anomalies. We suggest the presence of probable small-scaled (up to 4 m high) biogenic (palaeo-) build-ups composed mainly of coral colonies and bryozoans. Radiocarbon dating of three coral fragments show ages as old as 1897, 1985 and 1986 AD and suggests the presence of living *C. caespitosa* as close as 6 km to the phosphate treatment industry of Gabes at least until 1986 AD. This latter age coincides with the construction of the ammonium phosphate production plant, in 1979, in the Gulf of Gabes with an increase of the natural phosphate production. The higher impact of pollution on the marine environment in the inner part of the Gulf of Gabes likely induced the decline of *C. caespitosa*. This is well in

agreement with enhanced siltation processes suggested by the sedimentary facies and grain-size analyses presently characterizing the Gulf of Gabes nowadays.

Keywords: Ecology, Geochemistry

1. Introduction

Cladocora caespitosa is the only endemic zooxanthellate in the Mediterranean Sea. This coral species is a long lived coral species with the generation length estimated to be about 30 years (Casado-Amezúa et al., 2015) and can form banks at the present time (Morri et al., 1994). Live coral cover of *Cladocora caespitosa* in the Mediterranean Sea fluctuated in the last decade. Since 1999, this coral was exposed to several mass mortalities due to the warming events (Garrabou et al., 2009; Jiménez et al., 2014; Kersting et al., 2013a; Kružić et al., 2013; Perez et al., 2000; Rodolfo-Metalpa et al., 2005) and declined to 55% in some parts of the Mediterranean Sea (Casado-Amezúa et al., 2015). In addition to warming events, competition with invasive algae likely contributed to the mortality of this coral species (Kersting et al., 2015). Invasive algae were observed in different regions of Mediterranean Sea where living *C. caespitosa* are present (Kersting et al., 2014a; Kružić et al., 2012). The long life and the low natural mortality of this coral species buffer the low recruitment rates. When warming event in the Mediterranean Sea had a catastrophic impact on the mortality of *C. caespitosa* then the recruitment became critical and the recovery of the population difficult (Kersting et al., 2014b). Due to the disturbance regime of the Mediterranean Sea and *C. caespitosa* life history strategy, it was classified as an endangered species by the IUCN (International Union for Conservation of Nature) (Casado-Amezúa et al., 2015). One of the recommended actions of the IUCN is to extend the knowledge on the distribution and ecology of this species, especially at the localities where information is lacking.

In July 2014, an expedition to the Gulf of Gabes was organized to assess the impact of the local phosphate industry on the marine environment. The specific aims of the expedition were to collect data from seawater and living microfauna (benthic foraminifera) from surface sediments. Dead coral fragments belonging to the species *C. caespitosa* were collected. Such a discovery was unexpected since the presence of Recent to Sub-recent corals has been mentioned only south of the Kerkennah Islands (El Lakhrech et al., 2012). So far, no living and/or sub-fossil corals have been found or described in the vicinity of the wastewaters from the phosphate industry of Gabes.

The aims of this study are to document the presence of dead fragments of *C. caespitosa* in the inner part of the Gulf of Gabes and to evaluate the possible anthropogenic impact of the phosphate industry on their distribution. Data

collected on *C. caespitosa* during this expedition allows increasing the knowledge about this species in the region of the Gulf of Gabes as suggested by the IUCN.

2. Background

2.1. Oceanographic and environmental settings

The Gulf of Gabes is located in the south-western part of Tunisia and is delimited at north by the Kerkhenna Island and at south by Djerba Island. The Gulf is approximately 90 km wide (from Sfax to Djerba) and 100 km long (from Gabes to the open sea) (Fig. 1). It is mainly characterized by very shallow water depth with the isobaths of 50 m reached at 130 km from the coastline.

During the previous century, the Gulf of Gabes was considered as a nursery for many marine species. At the beginning of the 20th century, the majority of the seafloor of the Gulf of Gabes was covered by seagrass (Zaouali, 1993). *Posidonia oceanica* was the dominant seagrass species in the Gulf of Gabes and provided an ideal reproduction habitat for many species, including fishes and invertebrates (Aloulou et al., 2012).

Ben Brahim et al. (2010) estimated the loss of *Posidonia oceanica* cover in the Gulf of Gabes up to 90% since 1960. Several studies (Aloulou et al., 2012; Ayadi et al., 2014; Chouba and Mzoughi-Aguir, 2006; Darmoul et al., 1980; El Lakhrach et al., 2012; El Zrelli et al., 2015; Hamza and Bradai, 1994; Kharroubi et al., 2012; Rabaoui et al., 2014; Zairi and Rouis, 1999; Zaouali, 1993) show an impact of the phosphate industries on the marine environment: e.g., eutrophication of the basin, decreasing of the biodiversity, siltation of the seafloor, traces of heavy metals in the sediments and the tissues of some macrofauna (e.g., bivalves) and increasing of turbidity.

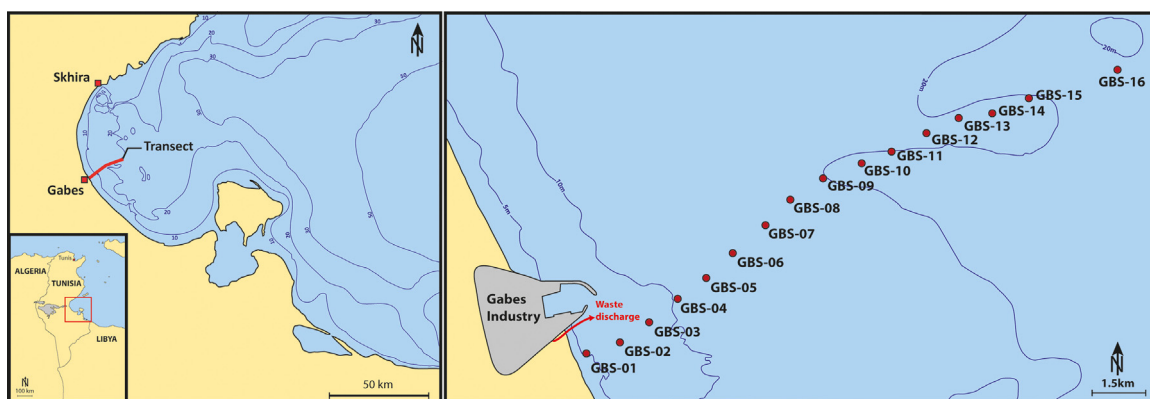


Fig. 1. (On the left) Location maps of the Gulf of Gabes with the position of the investigated transect. (On the right) Location of all the stations along the transect, the emplacement of the phosphate industry in Gabes and the waste discharge area.

2.2. Industrial phosphate treatment

The Gafsa Phosphate Compagny (CPG) is active in the Gafsa Basin and extracts the ore phosphate in seven open cast quarries and one underground mine (Galfati et al., 2011). The Tunisian Chemistry Group (GCT) exploits four industrial sites located in Sfax, M'Dhilla, Gabes and Skhira where they produce mainly phosphoric acid and fertilizers. In Gabes, the first industry plant for phosphoric acid production was created in 1972, followed by a second industry plant for diammonium phosphate production in 1979. A second industry plant for diammonium phosphate production was then created in 1985. The phosphate rocks are treated by sulfuric acid to produce phosphoric acid. This reaction generates a large amount of phosphogypsum (PG), which is considered as a waste product. The production of each ton of phosphoric acid generates 5 tons of PG (Zairi and Rouis, 1999). In Gabes, the totality of PG, which contains a high concentration of heavy metals, is directly discharged into the sea and generate a large area of pollution into the Gulf of Gabes (Ayadi et al., 2014; El Zrelli et al., 2015). For Gabes, the production of PG per day is estimated at 112'500 tons (Bejaoui et al., 2004). In addition to the PG, heated acid wastewaters with a high content of fluor are discharged directly into the sea next to the Gabes phosphate treatment industries causing a major environmental impact (Darmoul et al., 1980).

2.3. Ecology of *Cladocora caespitosa*

Thirty-three species of scleractinian corals are known in the Mediterranean Sea (Veron, 2000; Zibrowius, 1980). Among them, twenty-nine are azooxanthellate (lacking symbionts), one is typically zooxanthellate (symbiont bearing) (*Balanophyllia europaea*) and one is able to adapt to the azooxanthellate lifestyle (*Madracis pharensis*) (Veron, 2000). The family of *Cladocora caespitosa* has been revisited during the last few years. The genus was first excluded from Faviidae and included to Caryophylliidae (Romano and Cairns, 2000). In 2008, Fukami et al. (2008) included *C. caespitosa* in Oculinidae but it is now classified as Scleractinia incertae sedis and it is one of the zooxanthellate corals in the Mediterranean Sea (Leydet and Hellberg, 2015).

Cladocora caespitosa can develop on shallow (<10 m) and deeper (>30 m) rocky substrates and is able to thrive in turbid waters at relatively low irradiance mainly between 7 and 15 m depth. However in clear waters this coral can also be found down to 40 m (Peirano et al., 1999; Peirano et al., 2005; Schiller, 1993). As an adaptation to turbid environments, this coral has a high rate of mucus release and can rapidly and strongly alter feeding effort from autotrophy to heterotrophy (Hoogenboom et al., 2010). Calcification rates are similar with low and light intensity (Rodolfo-Metalpa et al., 2008). The colony is generally phaceloid, i.e. the

corallites develop vertically, and the coral branches build big irregular colonies, up to 1 m in diameter.

2.4. Distribution of *Cladocora caespitosa* in Mediterranean Sea

Cladocora caespitosa is present in the whole Mediterranean basin (Fig. 2). According to the OBIS (Ocean Biogeographic Information System) database, *C. caespitosa* occurs along the coasts of Spain, France, Italy, Croatia, Greece, Turkey, Lebanon, Israel, Egypt, Algeria, Morocco (Gibraltar Strait) and Tunisia. However, it has to be mentioned that the OBIS dataset is incomplete and that important information such as e.g., the source of the reports, the date of observations, and the indication if the documented corals were living or dead (fossil), are usually missing. For this reason, the dataset from OBIS should be used with caution. However, the database of the IUCN gives more information about the distribution of *C. caespitosa* and confirms the living record of this species in the different regions of the Mediterranean Sea. Living *C. caespitosa* have been observed in Greece, in Gulf of Atalanti (Laborel, 1987), along the Italian coast, in the Gulf of La Spezia (Morri, 2000; Peirano et al., 2001; Peirano et al., 2005; Rodolfo-Metalpa et al., 2005), along the Croatian coast (Kružić and Požar-Domac 2002; Kružić and Benkovic, 2008; Schiller 1993), in the Bay of Piran in Slovenia (Schiller, 1993), in the north-western Mediterranean Sea, along the Spanish coast (Kersting, 2013;

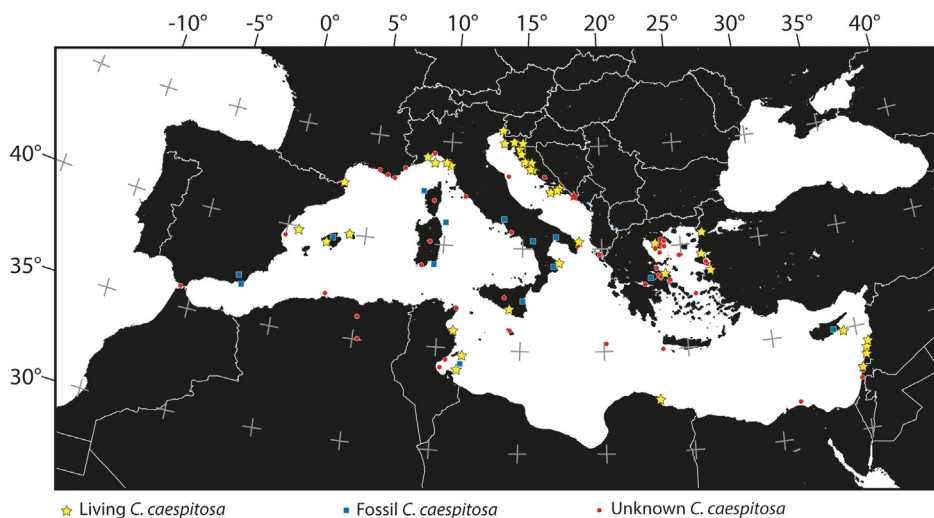


Fig. 2. Distribution of the living *C. caespitosa* (yellow stars), fossil *C. caespitosa* (blue square) and location of *C. caespitosa* where their state (living or fossil) is unknown (red circles) (OBIS (Ocean Biogeographic Information System), (Aguirre and Jimenez, 1998; Badalamenti et al., 2011; Bitar and Zibrowius, 1997; Casado-Amezúa et al., 2015; El Lakhraçh et al., 2012; Hoogenboom et al., 2010; Jiménez et al., 2014; Kersting, 2013; Kersting and Linares, 2012; Koukouras et al., 1998; Kružić and Požar-Domac, 2002; Kružić and Benkovic, 2008; Laborel, 1987; Montagna et al., 2007; Morri, 2000; Özalp and Alparslan, 2011; Peirano et al., 2001; Peirano et al., 2005; Peirano et al., 2009; Rodolfo-Metalpa et al., 2005; Rodolfo-Metalpa et al., 2008; Schiller, 1993; Zaouali, 1993; Zibrowius, 1980).

Kersting and Linares, 2012), along Cyprus coast (Jiménez et al., 2014) and along Turkish coast (Özalp and Alparslan, 2011). Large banks of the *C. caespitosa* have also been recorded in the Balearic Islands and Mallorca, and at Banyuls-Sur-Mer in France (Casado-Amezúa et al., 2015) and colonies have been found in Lebanon, North Israel and Libya (Badalamenti et al., 2011; Bitar and Zibrowius, 1997). However, the IUCN mentions the presence of living *C. caespitosa* along the Tunisian coast based on the work of Zibrowius (1980), which is the same reference as OBIS database. Supplementary recent references confirm the presence of living *C. caespitosa* in the Gulf of Trieste (Montagna et al., 2007) and in the Gulf of La Spezia in Italy (Hoogenboom et al., 2010; Rodolfo-Metalpa et al., 2008). Living colonies of *C. caespitosa* have been indicated in the Chalkidiki Peninsula in Greece (Koukouras et al., 1998). Peirano et al. (2009) indicate major fossil deposits in Spain, France, Italy, Tunisia, Greece and Cyprus. In addition, Aguirre and Jimenez (1998) mention fossil *C. caespitosa* south-eastern part of Spain. Living banks of *C. caespitosa* in Croatia and Greece was also mentioned by Peirano et al. (2009). Living *C. caespitosa* was also mentioned in the Gulf of Gabes in Tunisia (El Lakhrech et al., 2012; Zaouali, 1993) (Fig. 2).

Most studies on *C. caespitosa* have been carried out along the Croatian coast and Spanish coasts hosting a high density of living colonies (Fig. 2) (Casado-Amezúa et al., 2011; Casado-Amezúa et al., 2014; Kersting, 2013; Kersting et al., 2013a; Kersting et al., 2013b; Kersting et al., 2014a; Kersting et al., 2014b; Kersting et al., 2015; Kersting et al., 2016; Kružić and Benkovic, 2008; Kružić and Požar-Domac, 2003; Kružić and Požar-Domac, 2007; Kružić et al., 2012; Kružić et al., 2013). Some colonies in the Eastern part of the Adriatic Sea are particularly threatened by anthropogenic activities such as e.g., tuna farming (Kružić and Požar-Domac, 2007).

Based on the OBIS dataset, the occurrence of *C. caespitosa* along the Tunisian coasts is reported from three locations: one on the Eastern edge of Cap Bon and two from the Gulf of Gabes (Fig. 2). The latter two have the following localities: A) in front of the village of Mahres (34°27'00.00''N/10°37'01.20''E), B) in front of the city of Gabes.

Both reports from the Gulf of Gabes are however, not referring to living coral colonies. The location reporting corals in front of the village of Mahres is part from the dataset of the Smithsonian Institution National Museum of Natural History (NMNH) Invertebrate Zoology Collections. Based on the OBIS dataset, the corals found on this location, are from a core and can be considered as fossil. The corals reported in front of the city of Gabes are mentioned in the database of the "Hexacorallians of the world", which is linked to the thesis of Helmut W. Zibrowius "Les scleractiniaires de la Méditerranée et de l'Atlantique Nord-Oriental" (Zibrowius, 1980). Zibrowius (1980) mention the presence of

C. caespitosa in the Gulf of Gabes without any specific indication of the locality. Additionally, there are no indications if these corals were living, recent dead fragments or fossils. However, Peirano et al. (2009) mentioned that the fragments of *C. caespitosa* found in the Gulf of Gabes belong to a major fossil deposit. He also indicates the presence of living *C. caespitosa* in Monastir, in the southern part of the Gulf of Hammamet in Tunisia.

Recent articles, mention living *C. caespitosa* in the outer part of the Gulf of Gabes (El Lakhraich et al., 2012) (Fig. 2). Living specimens were reported from the Southeastern part of the Kerkenna Island at 26 to 32 m depth and on the Northeastern part of the Djerba Island at 30 to 35 m depth. Dead coral fragments were also found in the Northern part of the Gulf of Gabes (Zaouali, 1993) (Fig. 2). In conclusion, no recent dead corals and/or living *C. caespitosa* were mentioned, observed or described in the immediate proximity of the city of Gabes, as close as <20 km to the coast.

3. Materials and methods

Sediment samples were collected along an 18 km long transect in July 2014 (Fig. 1). The transect started next to the phosphate treatment industries at Gabes (0.4 km) and ended off shore (17.3 km) in the Gulf of Gabes (Fig. 1). Along the transect, 16 stations were sampled with a distance of approximately 1 km between each other. On each station an Ekman-Birge box core system (15 × 15 × 30 cm) was deployed to collect surface sediments. The sediments in the box core were described and the first centimetre depth of sediment was collected with a plastic spatula and stored in a plastic bottle. The location of the 16 stations was taken using a Global Positioning System (GPS) Garmin® 62S and the depth was measured with a Compass® echo sounder system.

Grain-size was performed on surface sediment samples by wet sieving. Bulk surface sediment samples were weighted, and their respective volume was measured before they were washed through five mesh-sieves: 500 µm, 250 µm, 125 µm, 63 µm and 32 µm. The grain size analysis could not be performed on sample GBS-03 because the sediment at this station was characterized by the presence of coarse and hard nodules.

The coral fragments for each sediment sample with a fraction higher than 500 µm mesh were picked, identified and counted with a Nikon SMZ18 binocular. The total number of coral fragments per sample was normalized with the total volume of sediment in order to compare values and determine the concentration of coral fragment for each station. Three radiocarbon dating were performed on coral fragments (Fig. 3; Table 1). Radiocarbon dating was performed at the Eidgenössische Technische Hochschule (ETH) Zürich using the accelerator mass spectrometry (AMS) technique. Around 50 mg of selected coral fragments were

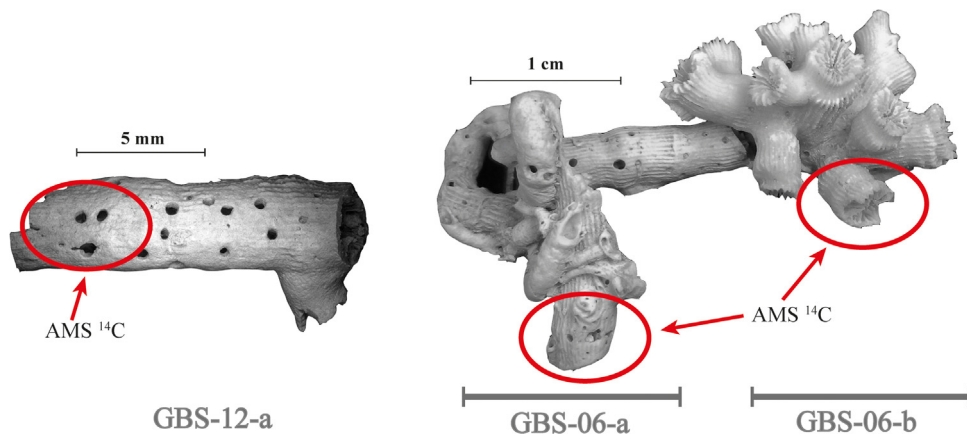


Fig. 3. (On the left) A strongly bioeroded coral fragment from station GBS-12. (On the right) The coral fragment from the station GBS-06. GBS-06-a makes the substratum for the coral with bioerosion trace and GBS-06-b is the very well preserved part of this coral fragment. The red circle is the part where the AMS ^{14}C analyses were performed.

treated by standardized chemical leaching procedure prior to measurement. The ^{14}C ages were corrected applying a reservoir age of 400 years and were calibrated (yr AD) using the software Oxcal v4.2.4. The post-bomb atmospheric NH_2 curve (Hua et al., 2013) was used to obtain the calibrated ages of samples GBS-06-a and GBS-06-b. Indeed, the modern fraction ($F^{14}\text{C}$) values of these samples indicate that they fall into the period 1950–2010 (Reimer et al., 2004; Hua et al., 2013). The Intcal13 atmospheric curve (Reimer et al., 2013) was used to obtain the calibrated ages (yr AD) for sample GBS-12-a.

Pictures of coral fragments were taken with a Digital 3D Micro-Macroscope Keyence VHX-600 ESO.

4. Results

4.1. Sedimentary facies and bathymetry

Based on the sediment descriptions and echo sounder data, a sedimentary profile of the 18 km long transect was established. Along the transect five different sedimentary facies were identified (Fig. 4):

- Sandy facies: This facies is present at stations GBS-01 and GBS-02. It is characterized by high quartz content and low biogenic fragments. The seafloor at station GBS-02 was covered by industrial sludge deposits.
- Carbonate nodule facies: This facies is present only at station GBS-03 (Fig. 4). Large nodules were found at this station forming a relatively hard substratum.
- Silty-sand facies: This facies is present at stations GBS-04, GBS-05 and GBS-06 (Fig. 4). It is characterized by high content of biogenic fragments (bryozoans,

Table 1. AMS ^{14}C ages obtained from the corals fragments.

Sample Number	Material	Calendar Ages (yr AD)				Cal. Ages used (yr AD)	Calibration curve
		Corr. ages ^{14}C ages (yr BP)	2σ Maximum	Intercepts	2σ Minimum		
GBS-06-a	<i>C. caespitosa</i>	-1476 ± 28	1984	1985	1986	1985	Hua et al., 2013
GBS-06-b	<i>C. caespitosa</i>	-1438 ± 28	1984	1986	1987	1986	Hua et al., 2013
GBS-12-a	<i>C. caespitosa</i>	7 ± 29	1877	1897	1918	1897	Reimer et al., 2013

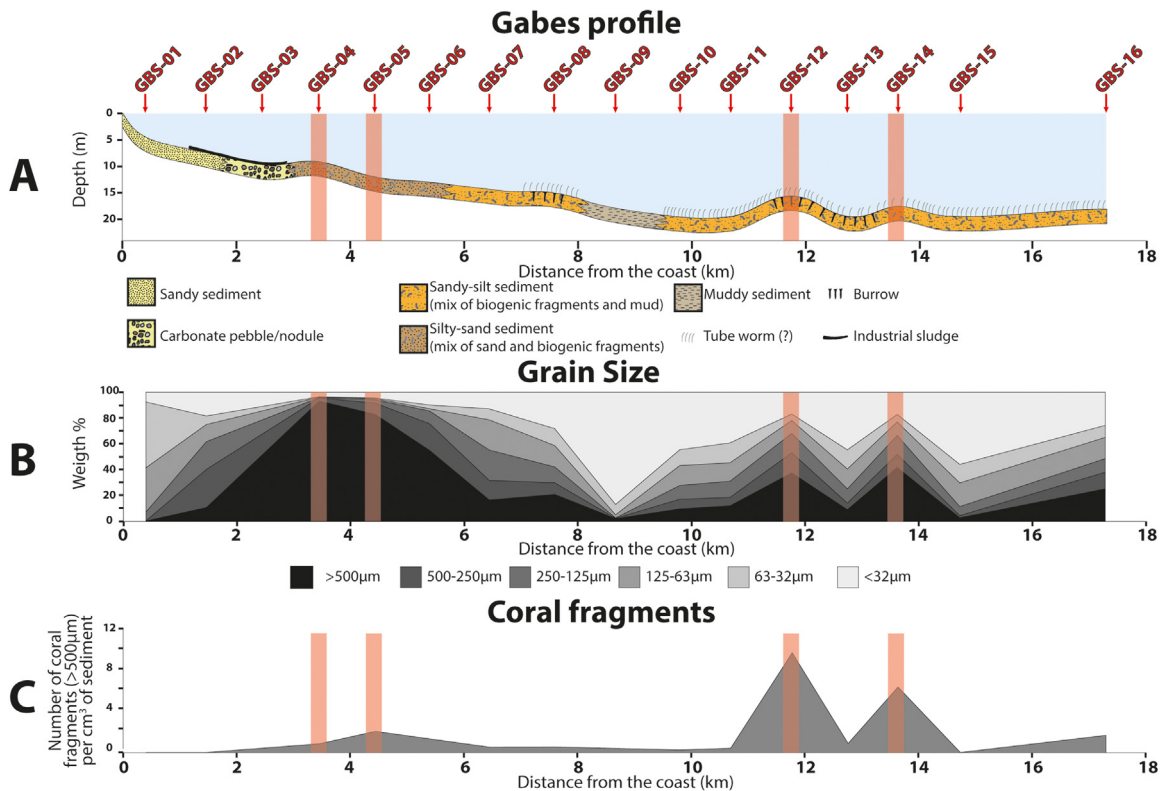


Fig. 4. (A) Depth as a function of the distance with the representation of the different sedimentary facies. (B) Grain size distribution along the transect. (C) Coral fragments distribution along the transect.

bivalves and gastropods) and sand (carbonate sand). Coral fragments are abundant especially at station GBS-05.

- Muddy facies: This facies is present only at station GBS-09 (Fig. 4). It is characterized by very high content of fine sediments (clay and silts).
- Sandy-silt facies: This facies is present at stations GBS-07, GBS-08, GBS-10, GBS-11, GBS-12, GBS-13, GBS-14, GBS-15 and GBS-16. It is characterized by a mix of biogenic fragments (bryozoans, bivalves and gastropods) and fine-grained sediments (clay). Many coral fragments were found, especially at stations GBS-12 and GBS-14 (Fig. 4).

Based on the echo sounder data, the maximum depth recorded along transect is 19.5 m, although some irregularities of the seafloor topography were observed (Fig. 4). The water depth did not increase continuously with the distance to the shoreline and a few stations clearly showed a positive seafloor topography exceeding over a few meters the surrounding sediments. This is the case especially for the stations GBS-12 and GBS-14 where the water depth reached respectively 15.4 and 17.6 m whereas the stations located before and after reached 19.5 m (Fig. 4). The general slope along the transect can be considered as very slowly

deepening because the maximum water depth reached 19.5 m depth at approximately 14.5 km from the coastline.

4.2. Coral determination

All *Cladocora caespitosa* fragments were collected on the seafloor (first centimeter of the sediment surface) along the transect of the working area. No living fragments were found or collected during the expedition. Coral fragments were mostly eroded and not well preserved; additionally bio-erosion was often present along the corallite wall. However, one fragment collected on the station GBS-06 appeared well preserved especially the calices part (Fig. 5). The dimensions of most *C. caespitosa* fragments had length spanning between 0.5 and 2 cm with only few fragments reaching 4 to 5 cm. Fragments presented a white coloration, with corallite diameter around 3 mm. Corallites had their own walls, were tubular and were compacted together forming clumps. Septa and pali presented spikes on their distal margins. Septo-costae were in two alternating orders, with only the first order reaching the columella. Columellae and paliform lobes were well developed.

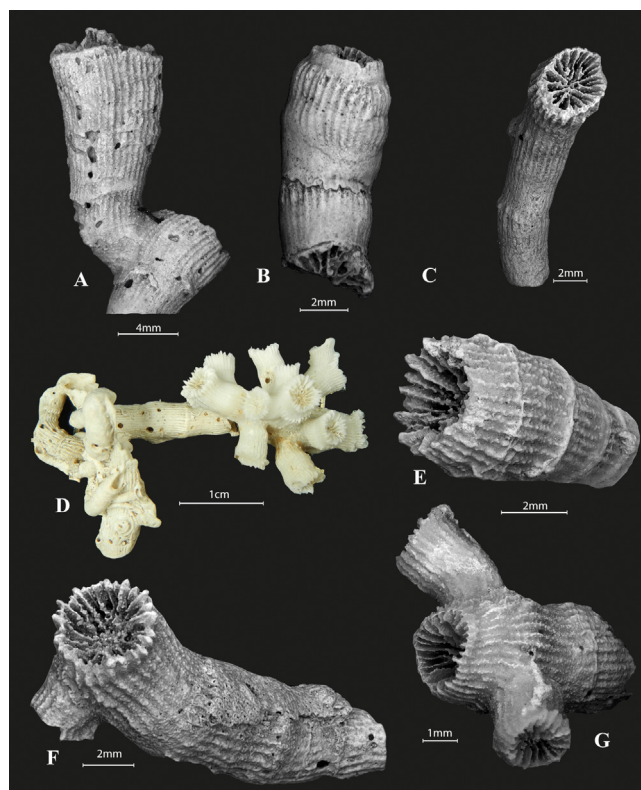


Fig. 5. A. *C. caespitosa* fragment from station GBS05; B. *C. caespitosa* with regrowth suture from station GBS-05; C. *C. caespitosa* fragment from station GBS-12; D. well preserved of *C. caespitosa* fragment from station GBS-06; E. *C. caespitosa* with growth pattern from station GBS-14; F. *C. caespitosa* fragment from station GBS-16; G. *C. caespitosa* fragment from station GBS-14.

Some samples showed sign of boring organisms associated with the coral skeleton. Growth patterns were present on the corallite wall for some *C. caespitosa* fragments (Fig. 5). Suture lines were visible on the circumference of the corallite wall and can be linked to an annual growth bands (Fig. 5).

4.3. Coral fragments quantification

A total of 660 coral fragments (>500 μm) were found in the samples from the transect. Most of the fragments were relatively small (<1 cm). Three fragments measured more than 2 cm, 23 fragments measured between 1 and 2 cm in length. The rest of the fragments were less than 1 cm long. For each station the number of coral fragments was normalized by the volume of sediment to facilitate comparison among the stations.

Two stations (GBS-12 and GBS-14) displayed a very high concentration of coral fragments, with respectively 9.97 and 6.55 coral fragments per cm^3 of sediment. These coral fragments from these previous stations were found respectively at the depth of 15.4 m and 17.6 m. Three stations (GBS-05, GBS-06 and GBS-16) had a relatively high concentration of coral fragments compared to the rest of the sample varying between 1.39 and 2.12 per cm^3 of sediment. These coral fragments from the previous stations were found respectively at the depth of 12 m, 12.9 and 18 m. For the rest of the stations, the number of coral fragments per cm^3 of sediment was lower than 0.90 (Fig. 4).

4.4. AMS ^{14}C dating

All coral fragments were characterized by important traces of bio- and physico-chemico erosion. However, one coral fragment of about 3 cm in length, recovered at station GBS-06, differs from all other fragments by its relatively good preservation with a fresh looking skeleton and intact calices and septa. The inferior part of this fragment, was however strongly bioeroded (Fig. 3). In total, three radiocarbon dating were performed on two coral fragments (Table 1).

From the two radiocarbon dating performed on the fragment from station GBS-06, one sample (GBS-06-a) was taken from the bioeroded section and one (GBS-06-b) from the well-preserved part (Fig. 3). The samples used for AMS ^{14}C dating were taken from the coral skeleton and the calices free of any external calcareous bioconstruction such as e.g., serpulids.

The AMS ^{14}C dating gave a relatively recent age for the coral fragment from the station GBS-06, with an age of 1985AD for GBS-06-a and 1986AD for GBS-06-b. They were post-industrial (Table 1). The coral fragment from station GBS-12 (GBS-12-a) was dated at 1897 AD and was on the other hand clearly of pre-industrial age (Table 1).

5. Discussion

5.1. Bathymetry of the Gulf of Gabes

The echo sounder data display a very gentle slope along the investigated transect, which is a main characteristic of the entire Gulf of Gabes. However some shoals were clearly observed during the sampling expedition (Fig. 4). These shoals measured between 0.5 to 4 m in height and were located on stations GBS-04, GBS-12 and GBS-14.

The processes behind the formation of the shoal in the Gulf of Gabes are still not clear and are a matter of discussion. A possible explanation for the formation of such positive structures may be related to biogenic build-ups. The grain-size shows a positive correlation with the shoals (Fig. 4). The coarse fractions are mainly composed of coral and other biogenic fragments such as e.g., bivalves, gastropods, bryozoans, echinoderms. In particular the high abundance of bryozoan fragments was observed between the stations GBS-05 and GBS-16 and in the fraction 500–250 μm . Bryozoans are well known as bioconstructor organisms and they are considered as important habitat-forming organisms (Goffredo and Dubinsky, 2013). Several bryozoan species are known to occur in the Gulf of Gabes: *Chartella papyracea*, *Margaretta cereoides*, *Pentapora fascialis*, *Reteporella grimaldii* and *Scrupocellaria scruposa* (El Lakhraich et al., 2012). However, only *Pentapora fascialis* occurs at similar water depths and in similar areas as *C. caespitosa* (south-eastern of Kerkennah Island at 26 m and north-eastern of Djerba Island at approximately 35 to 40 m water depth). Additionally, when the distribution of living *C. caespitosa* colonies (Fig. 2) is compared to the occurrences of habitat-forming bryozoans in the Mediterranean Sea (Goffredo and Dubinsky, 2013), several similarities can be recognized. Indeed, living *C. caespitosa* colonies are located in the same areas as the habitat-forming bryozoan *Pentapora fascialis*. This is particularly evident along the north-western Italian coast and along the Croatian coast. These two species live on similar substrates and similar water depths. Accordingly, we suggest that both corals and bryozoans formed the carbonate build-ups that are at the origin of the shoals observed during the expedition. Although *C. caespitosa* forms nowadays only relatively small colonies in the Mediterranean Sea i.e., the largest living bank found in the Mediterranean Sea is located in National Park Mljet at Veliko Jezeo, Croatia, and covers an area of 650 m^2 (Kružić and Požar-Domac, 2003), this coral formed extensive biogenic banks of several square kilometres during the Upper Pliocene (Aguirre and Jimenez, 1998). We tentatively suggest that the observed antiforms in the Gulf of Gabes are isolated carbonate built-ups formed by colonies of *C. caespitosa* and associated fauna. However, we are aware that the drilling of these structures is crucial to test our hypothesis.

5.2. *Cladocora caespitosa* and the pollution in the Gulf of Gabes

The PG discharged into the seawater next to the Gabes phosphate treatment industry contains several pollutants such as e.g., heavy metals, phosphorus, fluor, hydrocarbons and organic matter. The impact of pollution on the marine environment was well studied during the last twenty-five years and showed that heavy metals are present in the sediments with significant concentrations (Ayadi et al., 2014; Bahri et al., 2007; Chouba and Mzoughi-Aguir, 2006; Darmoul et al., 1980; Kharroubi et al., 2012; Rabaoui et al., 2014; Zaghden et al., 2014). The main impact of pollution in the Gulf of Gabes was the decline of the seagrass prairies, especially *Posidonia oceanica*, which was very abundant in the entire Gulf of Gabes at the beginning of the 19th century (Darmoul et al., 1980; Zaouali, 1993; Ben Brahim et al., 2010). A second major effect of the pollution in the Gulf of Gabes is siltation, which increases the turbidity in the water (Zaouali, 1993).

There are no records of living corals and ages reported so far in the recent literature near the phosphate industries of Gabes and thus arises the main question about the distribution of the corals through time and space. Are they post- or preindustrial and how is their distribution influenced by the anthropogenic forcing? The fact that most of the collected fragments are characterized by relatively severe erosion indicates that the corals are not actual. This is well supported by the radiocarbon dating giving clearly a pre-industrial age, and also by the relatively stressful ecological conditions prevailing in the entire Gulf of Gabes, which are rather unlikely to be conducive of scleractinian coral development. However, the AMS ^{14}C ages of the relatively well-preserved coral fragments found at station GBS-06 provide post-industrial ages and thus strongly suggest that corals occurred until very recent times in this area, contemporary to the industrial activity. Furthermore, we cannot exclude that still isolated small living colonies occur nowadays in the Gulf.

Based on the data collected during this research, we find it most probable that the pollution by the phosphate industry of Gabes caused the extinction of *C. caespitosa* within approximately 20 km around the waste discharge area. High turbidity has a direct impact on the penetration of the solar radiation in the seawater, creating a severe stress factor for zooxanthellate corals (Veron, 2000).

An additional factor, which could directly influence the distribution of *C. caespitosa* in the Gulf of Gabes, is siltation. Siltation of the seafloor in the Gulf of Gabes was described in previous studies (e.g., Zaouali, 1993) and was clearly observed during this sampling expedition. The seafloor from almost all stations is covered by a layer of fine-grained sediments. Rogers (1990) has demonstrated that extensive siltation in combination to low water energy causes the death of coral colonies.

Another important factor which can influence the decline of the *C. caespitosa* close to the waste discharge area is the increase of the water temperature. *C. caespitosa* is a species well adapted to the seasonal seawater temperature fluctuation in Mediterranean Sea (Kružić et al., 2013). However, *C. caespitosa* cannot well resist to an important increase of seawater temperature. Indeed, several masses mortality of coral in the Mediterranean Sea has been observed in coincidence with seawater warming (Kersting et al., 2013a; Rodolfo-Metalpa et al., 2005). One of mass mortality of the marine invertebrates in the Mediterranean Sea was recorded during the late summer 1999. This event was followed by an increase of 2 to 4 °C of the seawater and caused massive *C. caespitosa* mortality in the Northwestern Mediterranean (Perez et al., 2000; Rodolfo-Metalpa et al., 2005). Another important mass mortality event happened during the summer 2003 where *C. caespitosa* suffered of extensive tissue losses due to an exceptional warming episode (Garrabou et al., 2009; Kersting et al., 2013a). Several other mass mortality events happened afterwards as e.g., in the eastern Adriatic Sea in 2010 (Kružić et al., 2013) or in summer-autumn 2012 in the Levantine Sea (Cyprus) (Jiménez et al., 2014). Additionally, Kersting et al. (2013a) observed several mass mortalities of *C. caespitosa* in the Columbretes Islands (north-western Mediterranean, Spain) from 2002 to 2012 due to water thermal anomalies. Based on aquaria experiments and field observations, Rodolfo-Metalpa et al. (2005) shows that *C. caespitosa* is not able to resist to elevated seawater temperature for a long period (several weeks). Unfortunately, no monitoring data of the sea water temperature is performed in the Gulf of Gabes. However, Darmoul et al. (1980), observed in June 1978 that the waste water directly discharged into the sea had a temperature of 30.5 °C which is much higher than the normal seawater temperature (around 26 °C for seawater along the coastline and for the same period). This warm waste water comes from the cooling process of the sulfuric acid and from the wash water of the phosphate treatment. Up to 2 km around the discharge area, a thermal anomaly was clearly observed during May and June 1978. However, after several decades of waste water discharge and with a variation of the marine current due to the tides, thermal pollution has probably affected *C. caespitosa* and contributed to the decline of this species in this study area of the Gulf of Gabes.

Heavy metal pollution is a major problem for the marine environment. Heavy metals are considerate as serious pollutants because of their toxicity and because there are non-degradable in the environment (Pekey, 2006). Heavy metal enrichment in the marine environment is generally a sign of anthropogenic activities along the marine coast. Heavy metals can be introduced in marine environments through river, by waste deposits or waste discharge along the coast and can be incorporate into the sediment (Yu et al., 2008). Benthic organisms are exposed to these pollutants and can accumulate in soft tissues. Corals are able to accumulate heavy metals into the skeleton (David, 2003). Elevated levels of heavy

metals can cause an important number of stresses responses of corals: physiological stress; inhibition of coral fertilization and reduced reproductive success; decreased settlement and survival of coral larvae; changes in the population and growth of zooxanthellae; changes in the rate of photosynthesis resulted in a decrease in coral calcification and growth rates during the juvenile polyp stage; increased coral bleaching; enhanced coral mortality and lowered live corals; and outright mortality in associated invertebrates and fishes (Ali et al., 2011). Several studies show a high pollution by heavy metals due to waste discharge around the phosphate industrial sites of Gabes (Ayadi et al., 2014; Chouba and Mzoughi-Aguir, 2006; El Zrelli et al., 2015). El Zrelli et al. (2015) measured six heavy metal elements (Hg, Cd, Cu, Pb, Cr and Zr) in surface sediments along 20 km of the coast around the phosphate industries of Gabes. Zinc and cadmium concentrations in surface sediments reached 7165 and 950 ppm respectively close to discharge area. Mercury, copper, lead and chromium concentrations in the sediments reached lower values (0.045 ppm for Hg, 5.8 ppm for Cu, 4.9 ppm for Pb and 69.3 ppm for Cr). El Zrelli et al. (2015) detected heavy metals in surface sediments (concentrations of Pb, Cr, and Zn are around 14 ppm) in front of Zaratt which is located approximately 10 km south to the discharge area. Concentrations of the heavy metals in the surface sediments in front of Zaratt are significantly high and suggest a large area of pollution. Ayadi et al. (2014) also reveals high content of heavy metals in surface sediments around the phosphate industries in Gabes. Zinc reached up to 10175 ppm in the sediments close to the waste discharge area and the Cadmium reached up to 1225 ppm. The farthest off-shore station from the discharge area, which is to approximately 4 km from the coast line, recorded significant concentrations of heavy metals. Indeed, zinc content was still high with concentrations of 475 ppm, Cr content in surface sediment was around 37.5 ppm and copper and Cadmium exceeded 40 ppm. Heavy metal pollution by the phosphates industries in Gabes over several decades had likely an impact on *C. caespitosa* found next to the waste discharged area and it is not possible to exclude that this pollution source contributed to the decline of this coral species in this area of the Gulf of Gabes.

Corals are sensitive to water parameters. As showed previously, water temperature can influence coral health. Ocean acidification will lower carbonate accretions and coral calcification will decline dramatically if the carbon dioxide in the atmosphere continue to increase (Hoegh-Guldberg et al., 2007). Increase of CO₂ in the atmosphere released by anthropogenic activities has a direct impact on the seawater pH. Indeed the CO₂ combined with water produces carbonic acid. This process favors the dissolution of the coral skeleton and makes the calcification process unavailable for corals (Hoegh-Guldberg et al., 2007). However, acid release into seawater can have similar impacts on coral growth. Indeed, Marubini and Atkinson (1999) showed that the pH decrease had a negative effect on the growth rate of

Porites compressa when this species was incubating at a pH of 7.2. Additionally, Movilla et al. (2012) revealed that the calcification rate of *Oculina patagonica* and *C. caespitosa* decreased significantly under low pH (7.83) after only 92 days of experiment. Darmoul et al. (1980) demonstrated that the waste water coming from the phosphate industries of Gabes has a very low pH. Indeed, waste water pH reached 2.75 whereas the seawater pH along the coastline exceeded rarely 7.85. This pH anomaly of seawater was also observed by Ayadi et al. (2014) in 2010. The acid discharge by the phosphate industries impacts most likely on coral health and thus possibly contributed to the decline of *C. caespitosa* around the discharge area in the Gulf of Gabes. Signs of decalcification were investigated in each fragment, however, since most fragments presented a highly corroded surface with incrustation of serpulids or bryozoan it was not possible to draw any solid conclusions.

The post-industrial ages obtained for samples GBS-06-a and GBS-06-b imply that corals were living at the time of the initial phase of the phosphate industry of Gabes. The expansion of the industrial complex was mainly achieved in 1985 and was accompanied by a drastic increase in the production and in the final disposal of wastewaters into the Gulf. The gradual impact on the marine environment in response to the development of the industrial complex has been well demonstrated by the study of Darmoul et al. (1980) in the late 1970's. They showed that in 1978 *Posidonia* seagrass prairies and *Caulerpa* algae covered most parts of the Gulf with the exception of an azoic area located in the first 3 km in front of the industrial complex of Gabes. Already in 1990, Zaouali (1993) showed evidence for a total absence of seagrasses in the Gulf, which is also well confirmed by the video survey, performed in the frame of this study. Additionally, the production of natural phosphate increased significantly between 1980 and 1990, from 4.5 million of tons in 1980 to 6.3 million of tons in 1990. Before the construction of the second industry plant of ammonium phosphate production, the impact of the industry pollution on the marine environment was limited on the first three kilometres from the discharge area. These conditions likely allowed isolated coral colonies to grow close to the phosphate industry, at least at 6 km from the shore. We suggest that after the construction of the second industry plant of ammonium phosphate and the increase of the production of natural phosphate between 1980 and 1985, the discharge of waste products (wastewaters, industry sludge and PG) increased in parallel during this period. This resulted in a larger impacted area and led probably to the decline of *C. caespitosa* in the inner part of the Gulf of Gabes.

6. Conclusions

In the last 40 years, *Cladocora caespitosa* was observed several times in outer parts of the Gulf of Gabes. Some living corals are known to occur in the south-eastern of the Kerkennah Island and in the north-eastern part of Djerba Island

(El Lakhrach et al., 2012). However, this is the first study which documents coral fragments as close as 5 km to the shore off the Gabes phosphate treatment factories. Additionally, radiocarbon dating shows that corals occurred also during industrial times (1985).

The first stage (1972–1985) of the development of the Gabes phosphate treatment industries had an important impact on the marine environment but was limited to areas close to the industries (0 to 3 km from the shore). With the second industry plant of ammonium phosphate production in 1985 and the production increase of natural phosphate during the eighties, the pollution reached a larger area in the Gulf of Gabes and probably caused the decline of *C. caespitosa* in the inner part of the Gulf.

Declarations

Author contribution statement

Akram El Kateb, Claudio Stalder: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Christoph Neururer: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Chiara Pisapia: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Silvia Spezzaferri: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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