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Benthic Foraminifera as Proxies of Paleoenvironmental Changes in the Sant'Elia-Foxi Canyon (Gulf of Cagliari, Italy, Western Tyrrhenian Sea)

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Abstract: Marine coastal areas are highly dynamic and fragile environments characterised by a complex interplay of biological, physical, and chemical factors. These areas are also affected by anthropogenic activities with the discharge of organic and inorganic contaminants that alters the quality of the environment. In this work, the effects of anthropogenic activities (i.e., urban and industrial development) on benthic foraminifera have been investigated along the A2TM core collected from the Sant'Elia-Foxi Canyon (Gulf of Cagliari, Sardinia—western Tyrrhenian Sea). The Gulf of Cagliari has experienced intense urbanisation since the beginning of the twentieth century with the establishment of petrochemical complexes and harbour activities. The A2TM core, dating from 1907 to 2013, was analysed with an integrated approach that includes grain size, organic matter, and benthic foraminifera characterisation compared with geochemical characterisation. The variations in the composition of the benthic foraminiferal assemblages and the Margalef diversity index are related to the altered environmental conditions that reflect the historical development of the area and to the land-based activities surrounding the Gulf of Cagliari. The statistical analysis identifies two main intervals (i.e., the years 1907–1986 and 1986–2013) that are typified by different benthic foraminiferal assemblages and diversity values. Accordingly, the increases in organic matter content and both organic and inorganic contaminants are well mirrored by a major drop in foraminiferal diversity after 1973 and a major foraminiferal turnover after 1989. The composition of the benthic foraminiferal assemblages in the uppermost part of the core (i.e., 1989–2013) might suggest a lowering of the oxygen availability at the seafloor. These changes might be related to the increase in organic matter and the silty fraction in the same interval likely triggered by damming on land and wetland reclamation.

Keywords: pollution; urban development; continental margins; ecological quality status; biotic indices; deep sea

1. Introduction

The continental margins represent transition zones connecting terrestrial and coastal areas with deep-sea basins [1] and are characterised by high rates of sediment accumulation [2]. These margins are generally incised by submarine canyons that act as efficient conduits in delivering sediment, organic matter, and water masses from the continental shelf to the deeper environments [3,4]. Canyons are capable of conveying and/or sinking sediments along with particle-bound contaminants and organic matter and represent, therefore, a natural pathway connecting coastal to deep-sea ecosystems.

Since the last century, coastal areas have been increasingly threatened by human activities and the discharge of organic and inorganic contaminants leads to an overall deterioration of their environmental quality. Because of their persistency, contaminants can be transported far from their sources and marine sediments represent their final sink [5]. Due to the reduced physical and chemical dynamics of the deep-sea environments, many chemical contaminants represent a serious long-term threats to marine habitats and the benthic communities living therein [6]. In addition, the current climate change may also affect the hydrodynamic conditions as well as the supply of organic matter in both coastal and deep-sea ecosystems including sub-marine canyons [7]. These highly hydrodynamic and complex areas are also known for providing important ecological goods and services and have been defined as 'keystone structures' for greatly contributing to habitat heterogeneity [8,9]. The protection and restoration of continental and marine habitats as well as their evaluation in terms of ecological quality are regulated nationwide via the Water Framework Directive (WFD 60/2000) and Marine Strategic Framework Directive (MSFD 2008/56/EC) that also encourage EU member states to identify Biological Quality Elements (BQEs) and apply them for the evaluation of the Ecological Quality Status (EcoQS). In this context, benthic foraminifera, single-celled organisms, have been widely applied as proxies of (paleo)-environmental changes [10]. These marine organisms are small and abundant, have a widespread distribution from transitional marine to deep-sea waters, and have fossilisable shells (i.e., test) that are preserved in the records and enable us to determine the background conditions existing at the time of their deposition, making them valuable ecological proxies suitable for palaeoecological and palaeoenvironmental reconstructions [11–13].

Although the development of new technologies has advanced our knowledge on sub-marine canyons, we are far from fully understanding their oceanographic processes, biological communities, ecological roles, and potential impacts of land-based activities on them [14]. Because of it, additional studies, data, and information, particularly for community structure and ecosystem functioning, are required to effectively implement management and conservation plans [14]. Several foraminiferal investigations have been conducted within or close to submarine canyons; for a review see [15]. Most of them have, however, focused on the spatial distribution of living benthic foraminifera in relation to sedimentary disturbances (e.g., turbidite flows) [16–22] or material discharges (e.g., bauxite) [23].

The continental slope off the south of Sardinia (western Mediterranean Sea) with the occurrence of a multitude of sub-marine canyons represents a natural laboratory for investigating the effects of land-based pollutants on benthic communities (i.e., benthic foraminifera) and to understand their temporal variations. This study based on an integrated and multidisciplinary approach (micropaleontological, geochemical, sedimentological, and statistical analysis) aims to infer the paleoenvironmental changes and to identify land-based activities, triggering them in the Sant'Elia-Foxi canyon in the Gulf of Cagliari (Sardinia) in the last century.

2. Study Area

The Gulf of Cagliari (Sardinia, Italy, western Tyrrhenian Sea) extends between Capo Spartivento on the west and Capo Carbonara on the east and represents the progression of the southern part of the Sardinian Oligo-Miocene rift, in which the NW–SE Plio-Pleistocene Campidano graben overlapped [24–26]. It overlooks the continental margin of southern Sardinia, formed by a depositional system controlled by the Pliocene extensional tectonic and divided into various marginal basins [27]. The continental margin is made up of a shelf, slope, and several slope basins (i.e., intraslope Cagliari basin) that actively contribute to the sedimentation of the Sardinian–Algerian Abyssal Plain [28]. The continental shelf is well represented; indeed, it extends about 15–20 km south-eastward [28]. The shelf break is found at a depth ranging from 120 to 200 m [29], but it rises to shallower depths where the regressive erosion of canyons occurs at up to 60–80 m [30]. The continental slope is cut by different undersea valleys and tributary incisions, among these a system of canyons including Pula, Sarroch, Sant'Elia-Foxi and Carbonara are located (Figure 1).

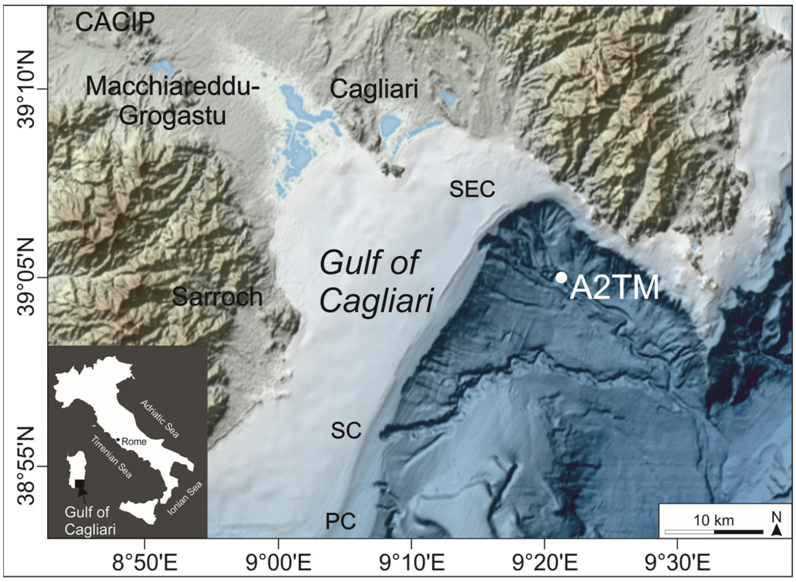

Figure 1. Map of the Gulf of Cagliari with the location of A2TM core in the Sant'Elia-Foxi canyon (SEC) along with the position of Sarroch Canyon (SC), Pula Canyon (PC), and Industrial Provincial Consortium of Cagliari (CACIP); modified after [6].

The shelf is covered by moderate terrigenous sediments from South Sardinia, particularly fluvial sediments derived from the alteration of the Palaeozoic metamorphic basement and from the Cenozoic sedimentary and volcanic rocks [31] and by a large amount of bioclastic material (mainly *Posidonia oceanica* and other marine phanerogams or algae in the inner-middle part) produced by the shelf itself [28]. The sediments are moved as hemipelagic muds and density turbidity currents from the shelf to the base of slope and basin floor. The entire coastal area of the Gulf of Cagliari is characterised by longshore currents that move sediments from the west to the east, while beaches like Poetto and Giorgino are also dominated by waves and littoral currents [32,33].

The city of Cagliari hosts about 150,000 inhabitants, but in the whole gulf area, it comprises over 500,000. The Gulf of Cagliari has been affected by a multitude of human-related activities, such as the building of Port of Cagliari in 1930, the establishment of Canal Harbour in the 1970, the presence of the Is Arenas wastewater treatment plant and the constitution of the CACIP (Industrial Provincial Consortium of Cagliari). The CACIP is a large industrial and petrochemical complex made up of three agglomerates covering an overall area of 9.244 ha of land: (a) the Macchiareddu–Grogastu area that undertakes fluorine treatment and the generation and distribution of propane and petrochemical plants; (b) the Sarroch industrial area in the western portion of the gulf with an oil refinery; and (c) the Elmas agglomeration. The industrial area of Sarroch falls within the site of national interest (SIN) of the Sulcis–Iglesiente–Guspinese established by the D.M. 468/2001. In the past, the area has been also affected by intense mining activities (Sulcis-Iglesiente). On the basis of the analyses of five sediment cores, [6] provided evidence of the historical impacts in the gulf during the last 110 years. Specifically, they revealed a marked increase in the content of silt likely triggered by damming on land coupled with a marked increase in Polycyclic Aromatic Hydrocarbons (PAHs), Pb, and Hg since 1930. Additionally, they documented higher values of Polychlorinated Biphenyls (PCBs) along with As and Hg since 1960, in response of the start of the industrial activity in the Sarlux–Saras refinery [6].

3. Materials and Methods

3.1. Core Sampling

A 33 cm thick sediment core (i.e., A2TM: Lat. 39°05′34″ N and Long. 09°21′29″ E) was collected within the Sant'Elia-Foxi Canyon in the Gulf of Cagliari at a water depth of 625 m during the Anomcity_2014 oceanographic survey on-board of the R/V Minerva Uno (National Research Council, CNR) (Figure 1). The core was retrieved with a 32 cm inner diameter cylindrical box-corer. Once on board, sub-cores were collected with a PVC tube of 10 cm for the different analyses and slices with an extruder at 0.5 cm intervals in the top 3 cm and for 1 cm at the bottom of the core. The sub-samples were placed in sealed polyethylene bottles and stored at +4 °C until analysis. No lamination structures were found, but a few macroscopic characteristics of bioturbation were observed in the upper 2–3 cm.

Analyses of geochemistry (i.e., PAHs, PCBs and trace elements), radioisotopes, and grain size were published in [6], and the reader may refer to this work regarding the methods used to measure these parameters. The present work provides new data on organic matter and foraminiferal assemblages. Additionally, the Pollution Load Index [34] was calculated, for which the background values were based on the lowest concentration of trace elements in the core.

3.2. Organic Matter

The TOC (total organic carbon) and TN (total nitrogen) analyses were conducted at the Laboratory of Oceanology and Geosciences in Wimereux (France). Sediment samples were first frozen and then freeze-dried; lastly, they were preserved at −20 °C at the laboratory. The TOC and TN were determined with an elemental analyser (ThermoFisher Flash 2000) and expressed as the % of C_{org} and N_{org} per total weight of dry sediment. The C/N ratio was calculated to infer the origin of the organic matter. The amount of inorganic carbon and nitrogen (measured in samples heated at 550 °C for 5 h) was subtracted.

3.3. Foraminiferal Analysis

Sediment samples for foraminiferal analyses were weighted on Kern EMB precision scale as bulk and then soaked for at least 24 h in a beaker with a solution of water and benzalkonium chloride, a detergent used to promote the disaggregation of the sediment. Sediments were then washed over a 63 μm nylon sieve to remove mud-size particles. The obtained residue was transferred on Munktell filter discs and then dried on a Cole–Parmer (model-4659) heating plate at 50 °C until the sample was thoroughly dry. Dried samples were reweighed and placed in previously labelled plastic bags, where they were stored until the examination. A total of 31 samples from the 33 cm length A2TM core were examined for benthic foraminifera using a stereomicroscope. The uppermost two (i.e., 0–1 and 1–1.5) samples were merged to obtain a representative weight. All benthic foraminiferal specimens were picked and used for taxonomical identification. Foraminiferal specimens were identified following the generic classifications of Loeblich and Tappan (1987) [35] and of other taxonomic works [36–39].

3.4. Statistical Analyses

The Margalef diversity [40] and the relative abundance of foraminiferal taxa were calculated. The latter was then used to group layers (i.e., years) by using a time-constrained hierarchical clustering analysis (HCA) along the core depth. A similarity tree was produced using the Euclidian distance. We used CONISS as agglomeration algorithm and clustering method [41]. The analysis was performed using the package vegan [42] and rioja [43] in RStudio (v. 2023). A principal component analysis (PCAs) was also performed considering environmental variables (e.g., grain size parameter) and geochemical indices (e.g., PAHs, PCBs, grain size, TOC, TOC/TN and PLI) as primary variables and the relative abundance of foraminiferal species (>3%) and Margalef diversity as secondary variables. Before statistical analyses, data were normalised by using an additive logarithmic transformation log(1 + X). Additionally, Spearman's Rho correlation was used to identify significant relationships between the factor score of PCA1 with the Margalef diversity and the relative abundance of foraminiferal species. The PCA and correlation analysis were performed using the software STATISTICA 13.5.

4. Results

4.1. Organic Matter

The TN (0.09%, as mean) and TOC (1.84%, as mean) contents ranged between 0.07 and 0.12%, with a mean value of 0.08% and between 1.4 and 2.62%, respectively (Figure 2 and Table S1). The TOC/TN ratio (20.8, as mean) varied between 18.49 and a maximum of 23.79 (Figure 2 and Table S1). The TN and TOC values increased along the core, particularly after 1973, whereas no changes were observed in TOC/TN values (Figure 2). The PLI (1.94, as mean) varied between 1.2 and 2.32.

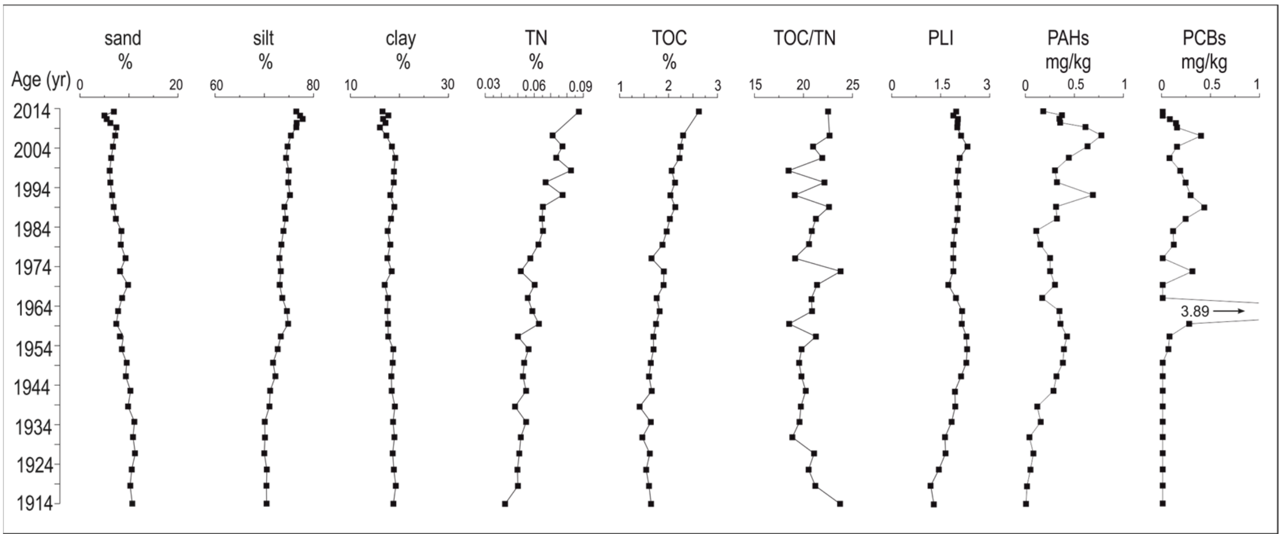

Figure 2. Grain size (i.e., sand, silt and clay and sand data from [6]), organic matter (TN: total nitrogen; TOC: total organic carbon; TOC/TN ratio) and geochemical (Pollution Load Index: PLI, Polycyclic Aromatic Hydrocarbons: PAHs; Polychlorinated Biphenyls: PCBs; data from [6]) parameter profiles along the A2TM core.

4.2. Benthic Foraminifera

A total of 137 benthic foraminiferal taxa has been identified. The most abundant taxa (>2%) were *Melonis affinis* (22.8%, as mean), *Bulimina marginata* (6.7%, as mean), *Hansenisca soldanii* (5.8%, as mean), *Uvigerina mediterranea* (4.8%, as mean), *Uvigerina* sp. (4.6%, as mean), *Melonis pompilioides* (4.5%, as mean), *Valvulineria bradyana* (2.9%, as mean), and *Uvigerina peregrina* (2.9%, as mean) (Table S2).

Changes in terms of relative abundance of taxa of the benthic foraminiferal assemblages can be observed along the core (Figure 3). The highest relative abundance of *B. marginata* occurred from 1919 to 1983. The same interval exhibited an increase in *Cibicides refulgens*, *Cibicidoides pseudoungerianus*, and *Cassidulina laevigata* (Figure 3). An overall decrease in the relative abundance of *Hansenisca soldanii* occurs along the core. Higher relative abundances of *U. mediterranea*, *Uvigerina* sp., *Uvigerina peregrina*, *C. laevigata*, *Elphidium complanatum*, and *Brizalina alata* were overserved after 1989. These changes were accompanied by a reduction in the relative abundance of *M. affinis*, *B. marginata*, *H. soldanii*, and *C. pseudoungerianus* (Figure 3).

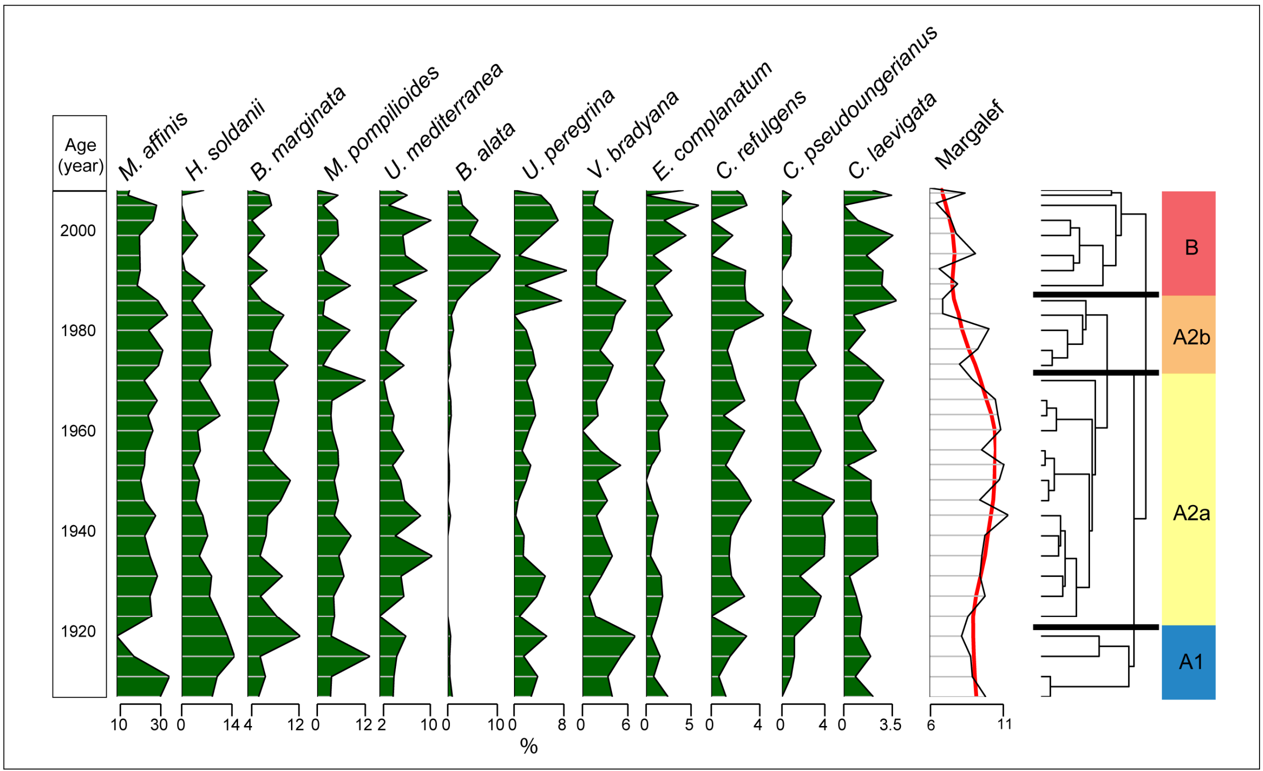

Figure 3. Hierarchical cluster analysis coupled with the plot of the relative abundance of foraminiferal taxa and the Margalef index along the different identified intervals (A1: 1907–1919; A2a: 1923–1970; A2b: 1973–1986; and B: 1989–2013) of the A2TM core. The red line represents the smoothed (5-point moving average) temporal variation of the Margalef index.

4.3. Statistical Analysis

The Margalef index showed mostly constant and relatively high values up to the early 1960s, then it progressively declined until the early 1980s (Figure 3). In the uppermost part of the core, namely from 1986 to 2013, the values of the Margalef index were constantly low and without significant variations (Figure 3). The HCA identified two main clusters: cluster A (~1907–1986) and cluster B (~1989–2013) (Figure 3). Cluster A can be further subdivided into two subclusters: Subcluster A1 corresponding to the 1907–1919 interval, while subcluster A2 can be further sub-divided in two intervals, A2a and A2b, corresponding to period ~1923–1970 and ~1973–1986, respectively (Figure 3).

The first subcluster A1 was mostly represented by *M. affinis* (21.5%, as mean), *H. soldanii* (11.1%, as mean), and *B. marginata* (7.1%, as mean) along with accessory taxa such as *Melonis pompilioides* (5.7%, as mean), *V. bradyana* (4.7%, as mean), and *U. mediterranea* (4.3%, as mean).

The subcluster A2a was mainly dominated by *M. affinis* (23.1%, as mean), followed by *B. marginata* (7.2%, as mean), *H. soldanii* (6.13%, as mean), *M. pompilioides* (5.2%, as mean), and *Uvigerina* sp. (4.1%, as mean), whereas the foraminiferal assemblages of subcluster A2b were characterised by the highest abundance of *M. affinis* (28.2%, as mean) in the records, followed by *B. marginata* (7.7%, as mean), *H. soldanii* (6.4%, as mean), and *U. peregrina* (4.6%, as mean) (Table S2). The most abundant taxa in cluster B differ from the sub-clusters A1, A2a, and A2b, as it is characterised by the lowest abundance of *M. affinis* (19.6%, as mean), *B. marginata* (5.2%, as mean), *H. soldanii* (2.3%, as mean), and the highest abundance of *Uvigerina* sp. (6.3%, as mean), *U. mediterranea* (5.8%, as mean), *B. alata* (5.1%, as mean), *U. peregrina* (4%, as mean), and *E. complanatum* (2.6%, as mean) (Table S2).

In the PCA, the first two components (i.e., axes) explained ~69.7% of the total variance (Figure 4). TOC, PLI, PCBs, PAHs, TN, and silt were strongly related to the first PCA component (ca. 55% of variance), which can be, therefore, interpreted as the environmental stress (ES) gradient (Figure 4A). On the other hand, the second PCA component, which only explained ca. 15% of the total variance, was related to TOC/TN and can be related to the quality of the organic matter. Some benthic foraminiferal species (e.g., *H. soldanii*, *M. pompilioides*, *H. elegans*, *S. columellaris*, *C. pseudoungerianus*, *G. altiformis*, *G. praegeri*, and *G. crassa*) and Margalef index were negatively correlated to the ES (Figure 4A, Table S3). An opposite trend was found for *B. alata*, *Uvigerina* sp., *E. complanatum*, and *H. balthica* (Figure 4A, Table S3). The PCA biplot ordered the layers (i.e., samples) mostly in chronological order (Figure 4B) and following the ES gradient.

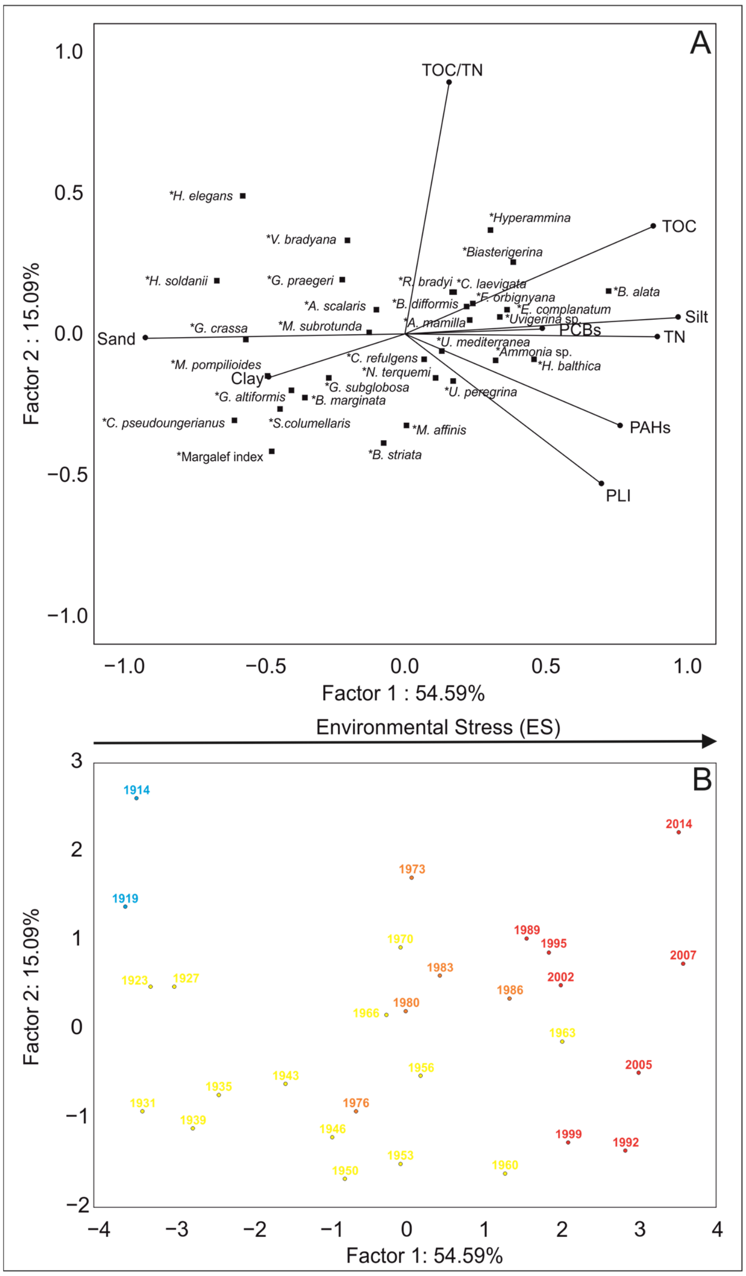

Figure 4. (**A**) R-mode and (**B**) Q-mode principal component analysis (PCA). Grain size parameters and geochemical indices are used as primary variables, and the relative abundance of benthic foraminiferal indices and Margalef index are used as secondary variables. The colour of the layers reflects the identified intervals (A1: 1907–1919—blue; A2a: 1923–1970—yellow; A2b: 1973–1986—orange; B: 1989–2013—red) by the Hierarchical cluster analysis along the A2TM core. The asterisk (*) marks the secondary variables used in the PCA.

5. Discussion

Based on a multidisciplinary investigation of the A2TM core covering the last 100 years, we here provide evidence of a significant shift in the benthic foraminiferal assemblages' composition in the Sant'Elia-Foxi Canyon within the Gulf of Cagliari (Sardinia—western Mediterranean Sea) that is an area that partly falls with the Italian SIN of Sulcis–Iglesiente–Guspinese.

Although the core was collected at a depth of 625 m under water and far from the land, canyons and seafloor morphology might represent the primary pathway for conveying sediments and associated contaminants. In light of this, we cannot rule out the possible transportation of benthic foraminiferal specimens from shallower areas; however, the benthic foraminiferal assemblages are strongly dominated by typical deep-sea species and the substantial absence of common shallow species, therefore the potential lateral transportation bias might be considered negligible. The variations in the composition of the benthic foraminiferal assemblages and the Margalef diversity index reflect the altered environmental conditions. These conditions have been related to the historical development of the area and to the land-based activities surrounding the Gulf of Cagliari. The HCA results in the identification of two main intervals (i.e., years 1907–1986 and 1986–2013) that are typified by different benthic foraminiferal assemblages and diversity values.

The entire core is characterised by high abundances (23%, as mean) of *M. affinis*. This taxon is mostly abundant in oxic conditions, but it has been also reported to be tolerant to dysoxic and suboxic conditions [44,45]. Another very abundant species is *H. soldanii*, an oxic taxon that has been recorded in well oxygenated, oligotrophic, and cold, deep water [46,47]. Consistently, this taxon has been found to show a negative correlation to the ES gradient underlying with coarser sediment (i.e., sand), lower values of pollutants (e.g., PLI, PAHs, and PCBs), and more importantly, of the organic matter (e.g., TOC and TN) as evidenced by the PCA. Based on *M. affinis* and *H. soldanii* abundance as well as the occurrence of epifaunal taxa thriving in well-oxygenated water such as *C. pseudoungerianus* and *C. refulgens* [45], no oxygen deficiency conditions occurred on the seafloor throughout the recorded period and, particularly, in the 1907–1923 interval (subcluster A1). In light of this and the PLI values, this interval would therefore represent mostly pre-anthropogenic conditions. The negative correlation between *C. pseudoungerianus* and ES confirms the ecological behaviour of this taxon. Despite this, a progressive decline in *H. soldanii* along the core and the lowest abundance of *M. affinis*, *C. pseudoungerianus*, and *C. refulgens* in the uppermost part of the core (i.e., 1989–2013: cluster B) might suggest a lowering of the oxygen availability at the seafloor. These changes are well mirrored by increases in the organic matter (i.e., TOC and TN) and the silty fraction within the same interval (cluster B). This change can be associated with damming activities on land [6]. The progressive decline in the availability of oxygen might be also supported by the increase in *C. laevigata* and *B. marginata* along the studied core in the 1923–1986 interval (subclusters A2a and A2b). A slight increase in diversity (i.e., Margalef index) values in the interval A2a might be related to the enhanced availability of organic matter (i.e., TOC) with relatively higher quality (i.e., lower values of TOC/TN). *Cassidulina laevigata* is a cosmopolite and a shallow infaunal species living in mesotrophic to eutrophic environments [48,49] with dependence on fresh phytodetritus supply [11]. Despite it declining in low-oxygen waters [50–52], this taxon is able to withstand hypoxic conditions [53] and has been included in the Ecological Group IV "Second-order opportunists" [54]. *Bulimina marginata* thrives in a wide range of marine environments, from the continental shelf [55] to the deep sea [56], and is widely used as an indicator species of low oxygen conditions, due to the tolerance of this taxon to anoxic conditions [57,58]. This species has been included in the Ecological Group III "Third-order opportunists" that encloses taxa tolerant to the first stages of organic enrichment [54].

The observed changes in the relative abundance of the benthic foraminiferal species along the core are certainly not only controlled by the oxygen availability at the seafloor but driven by a complex interplay of factors, including grain size, the quality and quantity of organic matter, and the sink of pollutants (i.e., trace elements, PAHs, and PCBs). These compositional variations are quite well mirrored in the historical development of the Gulf of Cagliari, where the initial activities started in early 1930s with the building of the Port of Cagliari and land reclamation driven by urban development, followed by a major phase of industrial development in the early 1960s (i.e., CACIP industrial complex) and the building of the Canal Harbour in 1970s [31]. Accordingly, a major increase in TOC and TN contents occurred after 1973 (subcluster A2b and cluster B) that corresponds well to the progressive decline of foraminiferal diversity. A gradual and constant increase in the quantity of organic matter (i.e., TOC and TN) has been observed along the A2TM core that is not, however, associated with any change in its quality (i.e., TOC/TN). The TOC/TN ratio varying between 18.49 and 23.79 is relatively high and suggests a terrestrial and anthropogenic origin of the organic matter [59–61].

The lowest values of diversity were found in the most recent interval, namely 1989–2013 (cluster B), which is also characterised by the highest contents of silt as well as of some contaminants (i.e., As, Zn, Cd, ΣPAHs, and partly ΣPCBs) (Figure S1). This interval also saw a major compositional shift in the benthic foraminiferal assemblages, as testified by the lowest abundance of *M. affinis* and *H. soldanii* coupled with the highest abundance of several species belonging to the genus *Uvigerina* (e.g., *U. peregrina* and *U. mediterranea*) and *C. laevigata. Cassidulina laevigata* and *U. peregrina* have been described as opportunistic taxa (i.e., tolerant to the first stages of organic enrichment and favoured by such conditions) [54,62,63]. *Uvigerina peregrina* is an infaunal species frequently related to sediments with a rich supply of organic matter and high concentrations of bacteria, as well as low oxygen conditions on the sea floor [45,64]. *Uvigerina peregrina* is also abundant in upwelling areas, characterised by the arrival of labile organic matter [65–67]. Interestingly, both *Uvigerina* sp. and *U. peregrina* are positively related to the ES gradient. Additionally, the 1973–2013 (subcluster A2b and cluster B) interval sees an increase in *V. bradyana*, a taxon commonly occurring in shelf areas and influenced by riverine input and high organic matter [68,69]. The same interval is characterised by a marked reduction in *Globocassidulina crassa* that adapted to decreased primary productivity [46] and was also supported by the negative relationship with ES as well as with TOC. This 1989–2013 interval (i.e., cluster B) saw a marked increase in *B. alata* that was positively related to the PCA1 and, therefore, with ES (e.g., TOC, TN, silt, PAHs, PCBs, and PLI). This taxon has been identified as an indifferent species (i.e., Ecological Group II) [54]. This group encloses taxa that are indifferent to the organic matter enrichment and occur in a wide range of organic matter but tend to disappear at very high concentrations [62].

Based on the geochemical data (e.g., PAHs, PCBs, PLI), the degree of contaminants shows a marked increase from the base of the core with a peak between 1946 and 1963. As already evidenced by [6], the increase in different contaminants is not simultaneous but strongly related to the development of anthropic activities on land. In particular, the first occurrence of PCBs was identified in the 1960s, as a consequence of the beginning of the industrial activity in the Sarlux–Saras refinery and the development of the large industrial and petrochemical complex (CACIP).

Since the concentrations of most of the analysed trace elements along with the ones of ΣPAHs and ΣPCBs are substantially below the ERL and definitively lower than ERM; thus, we infer that the observed changes in the composition of the benthic foraminiferal assemblages and reduction in diversity are likely related by a combination of pollutants with enhanced organic matter availability.

6. Conclusions

In the present study, benthic foraminifera were investigated along an A2TM core retrieved from the Sant'Elia-Foxi Canyon (Gulf of Cagliari, Sardinia—western Tyrrhenian Sea) in order to reconstruct the paleoenvironmental conditions and to evaluate the potential impact of human activities. The coastal area has been affected since the 1930s by progressive urbanisation (i.e., Port of Cagliari, Canal Harbour) and industrial development (i.e., CACIP complex) that caused a progressive change in the composition of the benthic foraminiferal assemblages and Margalef diversity values, as is supported by the geochemical record. Human activities, including dam construction, wetland reclamation, and port and channel constructions have altered the distribution and the quantity of fine materials and organic matter even in deep-sea (i.e., canyon) environments. These physical alterations have been accompanied by an increase in metals and organic compounds (i.e., PCBs and PAHs) even in locations very far away from their sources. The increases in organic matter content and contaminants are well mirrored by a major drop in foraminiferal diversity after 1973 and a major foraminiferal turnover after 1989. The composition of the benthic foraminiferal assemblages in the uppermost part of the core (i.e., 1989–2013) might suggest a lowering of the oxygen availability at the seafloor. These changes might be related to the increase in organic matter and the silty fraction in the same interval likely triggered by damming on land and wetland reclamation. This study reveals to what extent human activities and the related long-range transport of contaminates might have relevant effects on benthic communities in deep-sea ecosystems.

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