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Benthic foraminiferal assemblages and sedimentological characterisation of the coastal system of the Cagliari area (southern Sardinia, Italy)

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KEY WORDS - Living benthic foraminifera, grain-size analysis, environmental parameters, Gulf of Cagliari, Western Mediterranean Sea.

ABSTRACT - A survey of the coastal environment of Cagliari Harbour and the surrounding areas (southern Sardinia, Italy) has made it possible to study living benthic foraminiferal assemblages from 15 superficial sediments from the coastal system of the Gulf of Cagliari. This allowed a comparison of the distribution of recent living benthic foraminifera with sedimentological parameters to be done.

Foraminiferal density and species' richness are variable across the study area. The living assemblages are characterised by low diversity in the harbour and in the Santa Gilla Lagoon. In total, 95 different species were recognized, 18 of which being epiphytic, prefer an attached lifestyle, 54 are epifaunal and 23 infaunal. Epifaunal and epiphytic species such as Peneroplis pertusus *(Forskal, 1775),* Rosalina bradyi *(Cushman, 1915) and* Lobatula lobatula *(Walker & Jacob, 1798) are the main constituents of the living foraminiferal assemblages in the sandy sediment far from the harbour area and are associated with* Posidonia oceanica *(L.) Delile, 1813 seagrass. The low biodiversity values registered in some samples from this area can be related to the anthropogenic discharge of pollutants and fluctuating environmental parameters.*

Historical benthic foraminiferal assemblages from Cagliari Harbour, determined by H.B. Brady and published by Wright in 1871, have been reported for their historical value.

RIASSUNTO - [Caratterizzazione dei sedimenti e delle associazioni a foraminiferi bentonici del sistema costiero dell'area di Cagliari (Sardegna meridionale, Italia)] *- L'analisi di 15 campioni di sedimenti superficiali provenienti dall'area costiera del Golfo di Cagliari (Sardegna meridionale, Italia) ha permesso di confrontare la distribuzione delle associazioni dei foraminiferi bentonici viventi con le caratteristiche tessiturali e granulometriche dei sedimenti di fondo. La densità microfaunistica e l'abbondanza delle specie mostrano un'accentuata variabilità nei vari settori campionati, in particolare nel Porto di Cagliari e nell'area lagunare di S. Gilla. Nei sedimenti sabbiosi le biocenosi sono dominate da forme epifaunali e epifitiche come* Peneroplis pertusus *(Forskal, 1775),* Rosalina bradyi *(Cushman, 1915) e* Lobatula lobatula *(Walker & Jacob, 1798) associate a* Posidonia oceanica *(L.) Delile, 1813. In totale sono state riconosciute 95 specie, di cui 18 sessili (epifitiche), 54 epifaunali e 23 infaunali. I bassi valori di biodiversità registrati in alcuni campioni possono essere messi in relazione con l'impatto antropogenico particolarmente sensibile in alcune aree.*

Per il loro valore storico vengono riportati inoltre alcuni dati sulle associazioni a foraminiferi bentonici determinate da H.B. Brady e pubblicate da Wright (1877).

INTRODUCTION

The preliminary study of foraminiferal assemblages related to fine sedimentation in coastal areas is considered to be an important issue when it comes to evaluating the environmental quality of these regions, which are strongly influenced by anthropogenic action (e.g., Alve, 1991; Yanko et al., 1998; Debenay et al., 2001; Coccioni et al., 2003, 2005; Armynot du Châtelet et al., 2004; Pascual et al., 2008; Frontalini et al., 2009; Caruso et al., 2011; Schonfeld, 2012). Benthic foraminiferal studies of western Mediterranean basins are numerous and mainly focused on the distribution and ecology of species and assemblages (e.g., Colom, 1964; Blanc-Vernet, 1969; Vénec-Peyré & Le Calvez, 1981, 1988; Vénec-Peyré, 1984; Langer, 1988, 1993, 1998; Sgarrella & Moncharmont Zei, 1993; Frezza et al., 2005; Milker et al., 2009; Mateu Vicens et al., 2010; Buosi et al., 2012).

Understanding the impact of natural parameters on benthic foraminiferal distribution is a necessary prerequisite before describing anthropogenic impact. A precise knowledge on the various environmental parameters and their connected benthic foraminiferal community response is currently required. A better awareness of the mechanisms that determine the distribution of associations in natural environments will enable the use of foraminifera in environmental assessment to be promoted to decision-makers and governmental bodies. Indeed, the use of foraminifera as bioindicators of pollution in Italy was recently presented and summarised by Frontalini & Coccioni (2011).

As part of the European project MOMAR (Integrated System for Monitoring and Control of the Marine Environment), a monitoring survey of the coastal environments of Sardinia (Italy) has given us the opportunity to study living benthic foraminiferal

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assemblages. Within this project, the aim of our research is to investigate the effects of enhanced anthropogenic activities on living benthic foraminifera by analysing the composition, diversity and distribution of the assemblages. The MOMAR project has as its goal the development of a common system of marine environmental monitoring in Tuscany, Sardinia and Corsica. The project also aims to improve accessibility and cross-border cooperation with respect to the exploitation of natural resources through an integrated scientific plan. This will enable the coastal marine ecosystem and the pressures on it to be analysed in order to recognise the dynamics of environmental emergencies and to prevent them.

Specifically, harbours and dockyards are recognised as important locations where pollutants can be accumulated in sediments. Such changes constitute an environmental risk to aquatic life due to the potential uptake and accumulation of heavy metals in the biota (Vilela et al., 2004).

In this paper, we have illustrated the benthic foraminiferal distribution in the Cagliari area (southern Sardinia) and the foraminiferal associations collected in 1871 from the Harbour of Cagliari, determined by H.B. Brady and published by Wright in "The Annals and Magazine of Natural History" (Wright, 1877).

STUDY AREA

The Cagliari Harbour is situated in the south of Sardinia (Fig. 1). The continental shelf extends for 12 nautical miles towards the south and slopes slowly inside the Gulf of Cagliari, with wide sandy beaches, lagoons and littoral bars that are of Holocene age. The Gulf of Cagliari is a submerged extension of the Plio-Quaternary Graben of the Campidano (Pecorini & Pomesano Cherchi, 1969), which is in part superimposed on the Oligo-Miocene graben system and involves mainly reactivated normal faults (Cherchi & Montadert, 1982). At present, the depocentre still corresponds to the western area, which extends offshore into the Gulf of Cagliari and is visible on the onshore and offshore seismic profiles (Casula et al., 2001). In front of the harbour, the upper shoreface is characterised by both poor seagrass and an inclined shelf that is slightly convex, which extends as a continuation of the beaches to a depth of 3-8 meters (Fig. 1). The lower shoreface, meanwhile, is instead variously colonized by *Posidonia oceanica* (L.) Delile, 1813 and rhodophyceae algae. This unit is absent in front of the Cape S. Elia cliff, calcareous promontory of the Cagliari Gulf (Lecca et al., 2005). The Santa Gilla Lagoon is located on the west of Cagliari. It is an elongated, NW-SE oriented depression,

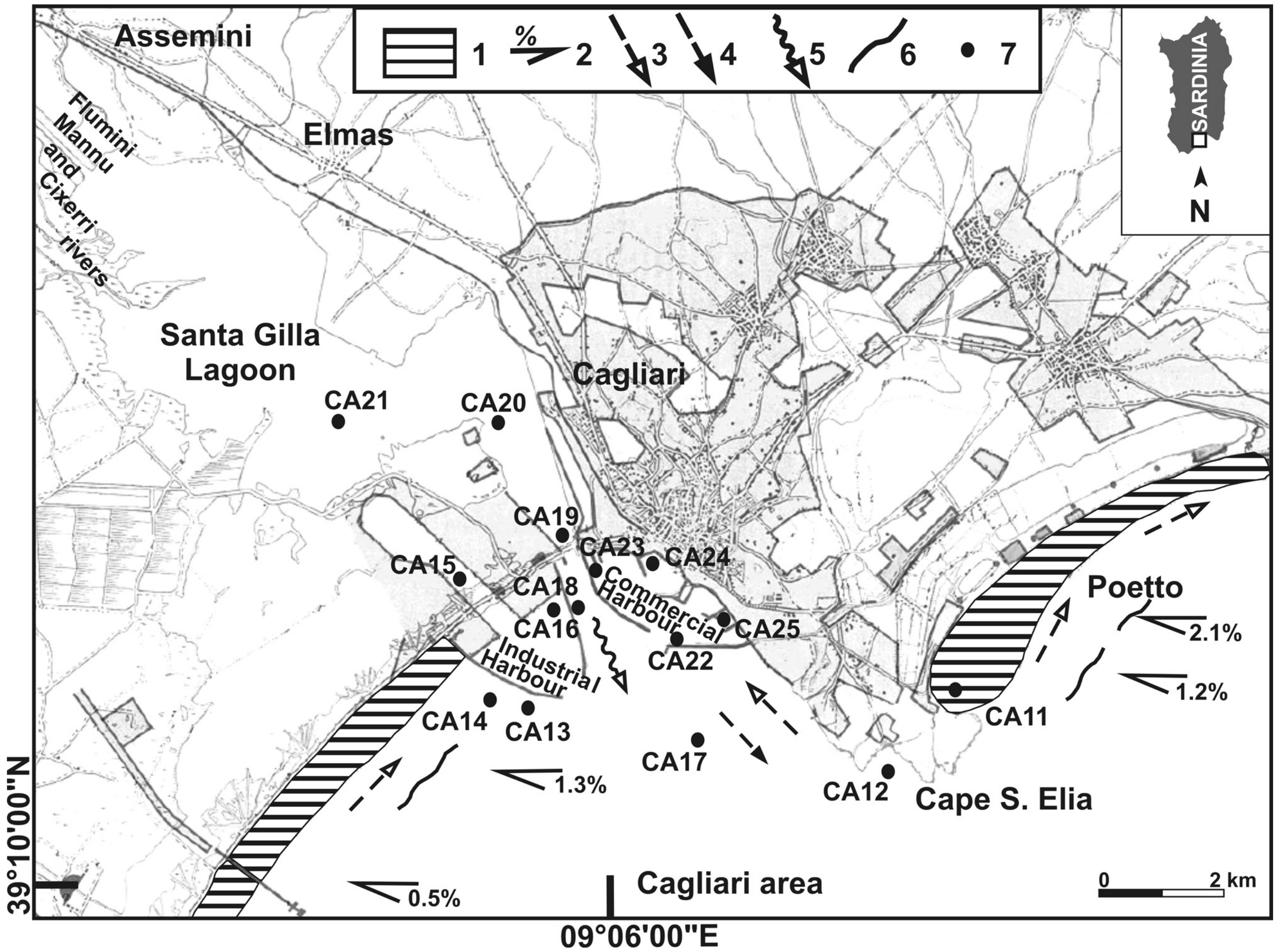

Fig. 1 - Study area, location of sampling stations: 1. Submarine beach (grain size mean 0.18-2.00 mm). 2. Seabottom slope (%) from shoreline to 5 m isobath. 3. Longshore drift. 4. Offshore drift. 5. Sediment supply: mainly fine sediment. 6. Latest mapped shoreline in sandy beach. 7. Sampling stations (after Di Gregorio et al., 1996; modified).

Sample	Depth (m)	% Gravel	% Sand	% Silt	% Clay	Sediment type
CA11	3	0.0	99.0	1.0	0.0	Sand
CA12	5	0.0	100.0	0.0	0.0	Sand
CA13	14	0.4	45.5	12.9	41.3	Slightly gravelly sandy mud
CA14	6	0.0	42.6	45.2	12.2	Sandy silt
CA15	15	2.3	43.8	20.9	33.0	Slightly gravelly sandy mud
CA16	4	3.6	77.7	11.0	7.7	Slightly gravelly muddy sand
CA17	13	5.2	94.5	0.20	0.0	Gravelly sand
CA18	5	7.8	69.8	14.3	8.10	Slightly gravelly muddy sand
CA19	2	38.2	29.8	7.6	24.4	Muddy gravel
CA20	3	20.7	5.5	24.9	48.9	Gravelly mud
CA21	2	9.7	3.9	24.8	61.6	Gravelly mud
CA22	8	0.9	38.5	29.5	31.1	Slightly gravelly sandy mud
CA23	9	3.2	62.4	27.1	7.3	Slightly gravelly muddy sand
CA24	9	2.4	48.4	26.5	22.7	Slightly gravelly sandy mud
CA25	7	1.5	28.8	65.3	4.40	Slightly gravelly sandy mud

Tab. 1 - Depth and grain-size classification (Folk & Ward, 1957) of examined samples.

roughly deltoid-shaped. In the south, it connects to the Mediterranean Sea through a narrow channel, and its extension is limited by a sand bar which sets the beach apart from the Gulf of Cagliari (Frontalini et al., 2009). On the northern shore, the lagoon has two major freshwater inflows from the Fluminimannu and Cixerri rivers (Fig. 1).

The study area is affected by pollution stress because of maritime and commercial traffic and the urban and industrial activities taking place immediately along the coast, as already evidenced by Contu et al. (1983), Degetto et al. (1997) and Schintu et al. (2009).

MATERIALS AND METHODS

This study is based on 15 surface sediment samples (about two cm depth) collected near the Cagliari Harbour (Fig. 1). The samples were obtained by means of a Van Veen grab sampler, and two aliquots from each sample were taken at each station and stored in polyethylene jars. The first was used for a thorough study of the benthic foraminiferal assemblages and the second for sedimentological analysis.

Samples for foraminiferal investigation were preserved in ethyl alcohol and treated with Rose Bengal (Walton, 1952) to distinguish living and dead specimens. In the laboratory, samples were washed with water through a 63 µm sieve. Three hundred stained specimens were selected from each sample and identified following the generic classifications of Loeblich & Tappan (1987).

Based on the living foraminiferal assemblages, biodiversity indices were extracted using the PAST statistical software (Hammer et al., 2001). These were then used as a tool to determine the general community structure of the studied area, with species' richness (number of species in a sample), foraminiferal density (FD is the number of specimens per one g of dry sediment) and Fisher-α indices being calculated (Hammer & Harper, 2005).

In order to obtain the particle size distribution of the inorganic components, the sediment samples were pre-dried, weighed and treated with 10% hydrogen peroxide (H_2O_2). Thereafter, the sediments were washed using a 63 µm sieve. The <6700 µm and >63 µm fraction was then further dry sieved through a battery of sieves spaced at 1/4 phi (ø) per unit. The <63 µm fractions were preserved and analysed using the pipette sedimentation method (Folk & Ward, 1957).

RESULTS

The bottom sediments are primarily composed of sand (~53%), with an average percentage of silt of 21% and clay 20%. When present, the coarser fraction is made up of gravel (6%, Tab. 1) mainly constituted of bioclasts (fragments of molluscs). Most of the samples that are located in peripheral sites in the Cagliari area (Cape S. Elia-Poetto) belong to the sand group (CA11, CA12 and CA17). Samples collected within the innermost part of the harbour area and the Santa Gilla Lagoon are composed of gravelly mud and slightly gravelly sandy mud. Only a few samples (CA16, CA18, CA19 and CA23) range from muddy gravel to slightly gravelly muddy sand.

The living faunas in the >63µm size fraction of the superficial sediment (0-2 cm) vary from station to station (Fig. 2), with 52 genera and 95 benthic foraminiferal species being observed. Of those, 18 prefer an attached lifestyle (epiphytic, permanently and temporarily attached), 54 are epifaunal and 23 are infaunal. Twenty-three species have a relative abundance greater than 5% in at least one sample (Tab. 2). Foraminiferal density (FD) varies from 0.55 at station CA14 to 31.07 at station CA11 (Poetto station). The species' richness is also variable, ranging from five species at station CA14 to 52 species at station CA17 (two km south of Cagliari Harbour). The Fisher-α index ranges from 1.10 in the CA14 sample (Cagliari Harbour) to 17.90 (CA17). In general, the fauna in the Cape S. Elia-Poetto stations (CA11, CA12 and CA17, Fig. 3a) is dominated by the porcelanaceous species *Peneroplis pertusus* (Forskal, 1775) (21%) and subordinately by *Ammonia beccarii* (Linnaeus, 1758) (13%) and *Rosalina bradyi* (Cushman, 1915) (6%). In this environment there is a predominance of epibenthic and epiphytic species like *Lobatula lobatula* (Walker & Jacob, 1798), *P. pertusus*, *P. planatus* (Fichtel & Moll, 1798) and *R. bradyi* due to the type of bottom sediments that are mainly composed of sand, associated with *P. oceanica* seagrass and located far away from the harbour area. In the Santa Gilla Lagoon stations (CA19, CA20 and CA21, Fig. 3b), *Ammonia tepida* (Cushman, 1926) (51%) is the most abundant species followed by *Bolivina spathulata* (Williamson, 1858) (15%), *Bolivina striatula* Cushman, 1922 and *Haynesina germanica* (Ehrenberg, 1840) (8%). The assemblages in the Cagliari Harbour (CA13, CA14, CA15, CA16, CA18, CA22, CA23, CA24 and CA25, Fig. 3c) are slightly different, being the main species *A. tepida* (18%), *B. spathulata* (12%) and *B. striatula* (11%). The associations of these last two areas consist mainly of opportunistic and infaunal species.

In a historical study from the Cagliari Harbour, Wright (1877) reported a diversified foraminiferal assemblage (Tab. 3) with 34 species belonging to 20 genera, with *Nubecularia lucifuga* Defrance, 1825, *Planorbulina*

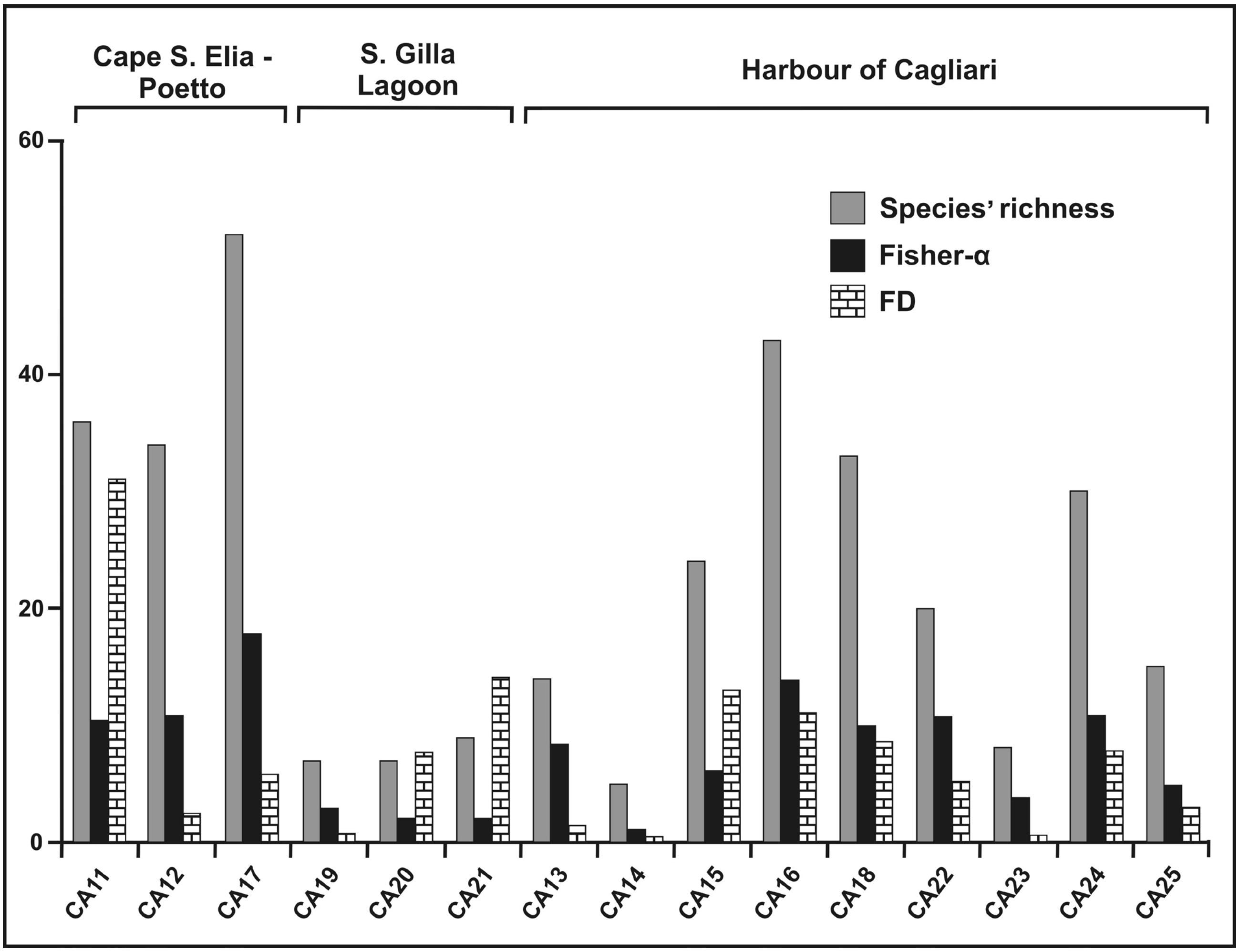

Fig. 2 - Biotic indices (Species' richness, Fisher-α index, foraminiferal density) from the Cagliari areas.

mediterranensis d'Orbigny, 1826 and *Pulvinulina vermiculata* Parker, Jones and Brady, 1871 as very common species in the Cagliari Harbour's sandy sediments. *Discorbina globularis* Karrer, 1877, *Quinqueloculina seminulum* (Linnaeus, 1758), *Quinqueloculina secans* d'Orbigny, 1826, *Peneroplis pertusus*, *Orbitolites complanata* Lamarck, 1801, *Textularia sagittula* Defrance, 1824, *Truncatulina tuberosa* Parker, Jones e Brady, 1871, *Rotalia beccarii* (Linnaeus, 1758), *Polytrema miniaceum* (Pallas, 1766), *Truncatulina lobatula* (Walker & Jacob, 1798) and *Polystomella crispa* (Linnaeus, 1758) are frequent as well. Unfortunately, the exact location of these historical sampling stations is not known to allow a more precise comparison with our data.

DISCUSSION

Studies of recent benthic foraminifera are numerous and go back to the mid-18th century. They provide a valuable and ever growing dataset on the distribution of modern benthic foraminifera (Schönfeld, 2012). Changes in the characteristics of benthic foraminiferal assemblages as a response to pollution have been discussed in many studies (e.g., Alve, 1991; Sharifi et al., 1991; Yanko et al., 1994, 1998; Samir, 2000; Samir & El-Din, 2001; Geslin et al., 2002; Coccioni et al., 2003, 2005; Armynot du Châtelet et al., 2004, 2011; Frontalini & Coccioni, 2008, 2011).

The benthic foraminiferal fauna from the Cagliari area reveals considerable levels of peculiarity. There are low species' richness and Fisher-α index values in the Santa Gilla Lagoon samples (mean values 7 and 2.35, respectively) as well as in some samples from the inner part of the Cagliari Harbour (lower values in CA14, 5 and 1.10, respectively). This agrees with most of the studies carried out in polluted harbours. For instance, the number of foraminiferal species retrieved in Joinville Harbor (Ile d'Yeu, France) by Debenay et al. (2001) ranged from 29 to 58. Armynot du Châtelet et al. (2004), meanwhile, reported between 4 and 34 species per sample in five harbours located in moderately polluted estuaries on the coast of Vendèe (France), whereas the species' richness of the living benthic foraminiferal taxa ranged from 1 to 12 species per sample in the port of Boulogne-sur-Mer (northern France, Armynot du Châtelet et al., 2011). Similarly, Martins et al. (2011) described <28 species per sample in the port of Aveiro (Portugal), while in Italy, Ferraro et al. (2009) found 17 benthic species in the Naples Harbour (southern Italy). In all of these areas the

	CA11		CA12		CA13		CA14		CA15		CA16		CA17		CA18		CA19		CA20		CA21		CA22		CA23		CA24		CA25	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%
Ammonia beccarii (Linnaeus, 1758)	0	0.00	60	25.53	0	0.00	0	0.00	0	0.00	0	0.00	42	13.59	1	0.38	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Ammonia inflata (Seguenza, 1862)	1	0.31	6	2.55	0	0.00	0	0.00	0	0.00	2	0.68	18	5.83	1	0.38	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Ammonia parkinsoniana (d'Orbigny, 1839)	20	6.25	9	3.83	0	0.00	0	0.00	0	0.00	2	0.68	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Ammonia tepida (Cushman, 1926)	1	0.31	0	0.00	5	13.89	19	18.18	38	12.75	52	17.75	6	1.94	44	16.73	13	44.83	30	51.72	97	57.06	9	15.52	4	14.81	32	20.00	32	31.68
Bolivina dilatata (Boomgart, 1949)	0	0.00	0	0.00	2	5.56	12	9.09	16	5.37	23	7.85	0	0.00	49	18.63	1	3.45	4	6.90	10	5.88	4	6.90	0	0.00	3	1.88	2	1.98
Bolivina spathulata (Williamson, 1858)	3	0.94	0	0.00	2	5.56	0	0.00	12	4.03	22	7.51	7	2.27	16	6.08	6	20.69	9	15.52	15	8.82	7	12.07	10	37.04	28	17.50	10	9.90
Bolivina striatula Cushman, 1922	0	0.00	0	0.00	5	13.89	51	45.45	24	8.05	24	8.19	2	0.65	35	13.31	5	17.24	0	0.00	9	5.29	0	0.00	3	11.11	5	3.13	5	4.95
Bulimina elongata d'Orbigny, 1826	0	0.00	0	0.00	0	0.00	0	0.00	9	3.02	7	2.39	1	0.32	2	0.76	0	0.00	0	0.00	0	0.00	4	6.90	5	18.52	10	6.25	1	0.99
Bulimina marginata d´Orbigny, 1826	0	0.00	0	0.00	0	0.00	0	0.00	7	2.35	2	0.68	0	0.00	1	0.38	0	0.00	0	0.00	0	0.00	3	5.17	0	0.00	2	1.25	1	0.99
Fursenkoina acuta (d'Orbigny, 1846)	0	0.00	0	0.00	0	0.00	18	18.18	13	4.36	20	6.83	0	0.00	7	2.66	1	3.45	0	0.00	2	1.18	2	3.45	0	0.00	4	2.50	34	33.66
Haynesina germanica (Ehrenberg, 1840)	23	7.19	0	0.00	0	0.00	0	0.00	8	2.68	34	11.60	2	0.65	4	1.52	2	6.90	3	5.17	19	11.18	2	3.45	1	3.70	0	0.00	0	0.00
Hopkinsina pacifica Cushman, 1933	0	0.00	0	0.00	0	0.00	0	0.00	121	40.60	15	5.12	0	0.00	2	0.76	0	0.00	0	0.00	0	0.00	5	8.62	1	3.70	3	1.88	3	2.97
Lobatula lobatula (Walker & Jacob, 1798)	9	2.81	14	5.96	0	0.00	0	0.00	0	0.00	0	0.00	9	2.91	2	0.76	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	1	0.63	0	0.00
Nonionoides turgida (Williamson, 1858)	0	0,00	0	0.00	6	16.67	0	0.00	26	8,72	0	0.00	1	0.32	0	0.00	0	0.00	0	0.00	0	0.00	2	3.45	0	0.00	0	0.00	2	1.98
Peneroplis pertusus (Forskal, 1775)	79	24.69	45	19.15	0	0.00	0	0.00	0	0.00	0	0.00	64	20.71	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Peneroplis planatus (Fichtel & Moll, 1798)	1	0.31	13	5.56	0	0.00	0	0.00	0	0.00	0	0.00	14	4.53	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Planorbulina mediterranensis d'Orbigny, 1826	1	0.31	1	0.43	0	0.00	0	0.00	1	0.34	0	0.00	1	0.32	3	1.14	0	0.00	0	0.00	0	0.00	3	5.17	1	3.70	1	0.63	0	0.00
Quinqueloculina laevigata d´Orbigny, 1839	29	9.06	3	1.28	0	0.00	0	0.00	2	0.67	6	2.05	5	1.62	16	6.08	0	0.00	0	0.00	13	7.65	2	3.45	0	0.00	12	7.50	3	2.97
Quinqueloculina seminula (Linnaeus, 1758)	17	5.31	0	0.00	1	2.78	0	0.00	0	0,00	1	0.34	7	2.27	0	0.00	1	3.45	8	13.79	0	0.00	3	5.17	0	0.00	1	0.63	0	0.00
Quinqueloculina stelligera Schlumberger, 1893	49	15.31	0	0.00	7	19.44	0	0.00	5	1.68	15	5.12	0	0.00	23	8.75	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	4	2.50	0	0.00
Quinqueloculina ungeriana d´Orbigny, 1846	6	1.88	14	5.96	0	0.00	0	0.00	0	0.00	3	1.02	4	1.29	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Rosalina bradyi (Cushman, 1915)	15	4.69	19	8.09	0	0.00	0	0.00	0	0.00	3	1.02	14	4.53	5	1.90	0	0.00	0	0.00	0	0.00	2	3.45	0	0.00	4	2.50	0	0.00
Sigmoilina costata Schlumberger, 1893	5	1.56	2	0.85	1	2.78	0	0.00	0	0.00	1	0.34	3	0.97	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	1	0.63	0	0.00
No. specimens	320		235		36		115		298		293		309		263		29		58		166		58		27		160		101	

Tab. 2 - List of species with relative abundance greater than 5% in at least one sample.

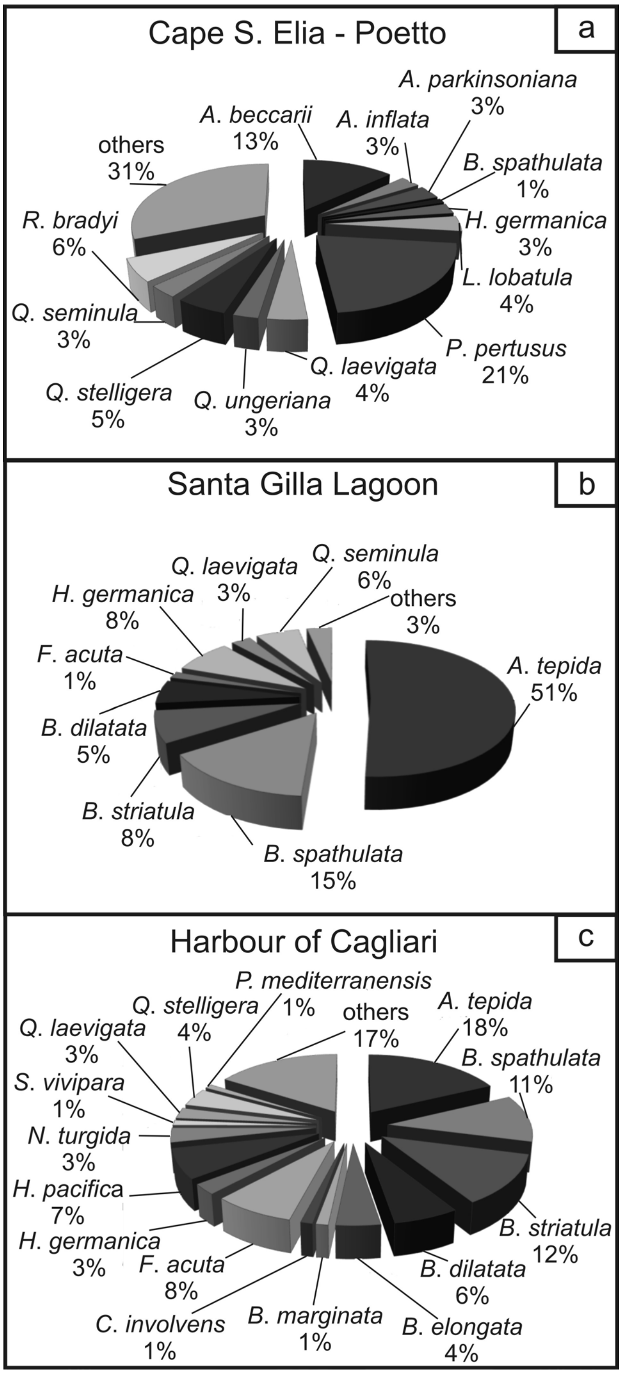

Fig. 3 - Relative abundance of species in a) Cape S. Elia-Poetto stations, b) Santa Gilla Lagoon stations and c) Cagliari Harbour stations.

low diversity value is attributed to high metal and PAHs (Polycyclic Aromatic Hydrocarbons) concentrations that modify the foraminiferal habitat.

The entire Cagliari Harbour area has directly or indirectly undergone severe environmental stress caused by commercial-maritime traffic and urban and industrial centres that are immediately located along the coast, as already evidenced by some research (e.g., Contu et al., 1983; Degetto et al., 1997; Schintu et al., 2009). The foraminiferal distribution in the studied area is mainly influenced by factors related to environment, depth and grain-size parameters. In particular, the Santa Gilla Lagoon has been subjected to industrial discharges of mercury, lead and zinc compounds, as well as municipal untreated sewage, for several decades (Degetto et al., 1997) and these results were confirmed by other investigations (Contu et al., 1983, 1984, 1985). Frontalini et al. (2009) reported that this transitional environment is notably affected by trace element content, in particular Cr, Cu, Hg, Ni, Pb and Zn. Mercury, meanwhile, has values up to ten times higher than the background level. According to Contu et al. (1984) and Frontalini et al. (2009), high heavy metal concentrations depend on their accumulation in the muddy sediment and in the organic matter fraction from previous decades. Moreover, Contu et al. (1983) have found maximum concentrations of oils and heavy metals in the industrial and commercial harbour areas. According to these authors, the values decrease towards Cape S. Elia (calcareous promontory of the Cagliari Gulf).

The results presented above indicate that there is a different sediment texture in the examined areas that influences the distribution of living benthic foraminifera. In the sandy sediments, the dominant biocoenosis comprised epiphytic and epifaunal species belonging to *P. pertusus*, *A. beccarii* and *R. bradyi*. *P. pertusus* and *R. bradyi* are widespread, with notable abundance on the bottoms with vegetation cover, particularly on *Posidonia* leaves and rhizomes (Langer, 1988). According to Langer (1993), *P. pertusus* is a permanently motile and grazing epiphyte, whereas *R. bradyi* possesses an attachment surface but is predominantly motile (Langer, 1993). *Ammonia beccarii* is also very widespread, and is generally abundant in the entire infralittoral zone, especially in the first 30 m, which is mostly on the sandy bottom (Sgarrella & Moncharmont Zei, 1993). On the other hand, in the muddy sediments, the foraminiferal assemblages are different, becoming predominantly opportunistic with infaunal species like *A. tepida*, *H. germanica* and bolivinids. *A. tepida* is a common species that is usually found in brackish environments with a salinity less than 33‰ (Debenay et al., 1998) and is known for its high tolerance to very polluted environments and high concentrations of heavy metals and hydrocarbons (e.g., Setty & Nigam, 1984; Yanko et al., 1994; Armynot du Châtelet et al., 2004; Ferraro et al., 2006; Frontalini & Coccioni, 2008; Frontalini et al., 2009). *H. germanica*, meanwhile, is an extremely euryhaline species that is tolerant of very restricted conditions (e.g., Murray, 1991; Alve & Murray, 1999; Pascual et al., 2002; Debenay, 2009), and several authors (e.g., Stubbles, 1993; Alve & Murray, 1994; Armynot du Châtelet et al., 2004; Frontalini et al., 2009) have reported that it may also be tolerant to high inputs of organic matter, heavy metals and hydrocarbons. Bolivinids are known to survive in oxygen-deficit environments (Bernhard, 1986; Murray, 1991; Debenay, 2009). In polluted areas these species are found in high proportions in muddy sediments, where they are resistant to metal and other chemical pollution. Examples are: Port Joinville Harbor (Ile d'Yeu, France), where the nature of the sediment has a great influence on bolivinids and strong pollution is indicated by the tolerant pioneer species *Cribroelphidium excavatum* (Terquem, 1875) and *H. germanica* (Debenay et al., 2001); Boulogne-sur-Mer Harbour (northern France, Armynot

Species determined by H.B. Brady	Abundance
Biloculina ringens Lamarck	rare
Triloculina trigonula Lamarck	rare
Triloculina oblonga Montagu	somewhat rare
Triloculina brongniartiana d'Orbigny	rare
Quinqueloculina seminulum Linnè	common
Quinqueloculina secans d'Orbigny	common
Quinqueloculina subrotunda Montagu	rare
Spiroloculina limbata d'Orbigny	somewhat rare
Spiroloculina excavata d'Orbigny	somewhat rare
Nubecularia lucifuga Defrance	very common
Peneroplis pertusus Forskal	common
Peneroplis arietinus Batsch	rare
Orbitolites complanata Lamarck	common
Vaginulina legumen Linnè	rare
Cristellaria crepidula Fichtel & Moll	rare
Polymorphina gibba d'Orbigny	rare
Polymorphina compressa d'Orbigny	rare
Polymorphina communis d'Orbigny	rare
Textularia sagittula Defrance	common
Textularia agglutinans d'Orbigny	less common
Discorbina globularis d'Orbigny	somewhat common
Discorbina rosacea d'Orbigny	rare
Planorbulina mediterranensis d'Orbigny	very common
Truncatulina lobatula Walker & Jacob	common
Truncatulina refulgens Montfort	rare
Truncatulina tuberosa Fichtel & Moll	common
Pulvinulina concentrica Parker & Jones	rare
Pulvinulina vermiculata d'Orbigny	very common
Rotalia beccarii Linnè	common
Tinoporus laevis Parker & Jones	rare
Polytrema miniaceum Linnè	common
Nonionina asterizans Fichtel & Moll	rare
Nonionina depressula Walker & Jacob	rare
Polystomella crispa Linnè	common

Tab. 3 - List of species and their relative abundance as reported by Wright (1877).

du Châtelet et al., 2011), where the benthic foraminifera *H. germanica* and *Bolivina pseudoplicata* Heron-Allen & Earland, 1930 were found to live particularly well within the innermost parts of the harbour basins, where the highest concentrations of organic carbon and heavy metals occur; and the Lagoon of Venice (Italy, Coccioni et al., 2009), where the biocoenosis is dominated by *A. tepida*, *H. germanica* and *Cribroelphidium oceanensis* (d'Orbigny, 1826) and subordinately by *Aubignyna perlucida* (Heron-Allen & Earland, 1913), *Ammonia parkinsoniana* (d'Orbigny, 1839) and *B. striatula*.

The historical benthic foraminiferal assemblages described by Wright (1877) are quite different. Indeed, the author reported that the very common species in these sandy sediments were: *Nubecularia lucifuga*, *Planorbulina mediterranensis*, *Pulvinulina vermiculata* and *Discorbina globularis*, followed by *Spiroplectammina sagittula* (Defrance, 1824) (reported as *Textularia sagittula*), *Cibicides tuberculata* Natland, 1938 (reported as *Truncatulina tuberosa*), *Ammonia beccarii* (reported as *Rotalia beccarii*), *Miniacina miniacea* (Pallas, 1766) (reported as *Polytrema miniaceum*), *Lobatula lobatula* (reported as *Truncatulina lobatula*) and *Elphidium crispum* (Linnaeus, 1758) (reported as *Polystomella crispa*). These benthic assemblages are probably related to a natural environment that was significantly different from that of the present day. Unfortunately, the grain-size and environmental parameters of these historical sampling stations are not known for allowing a comparison with our data.

The actual decrease of species' richness, Fisher-α index values and foraminiferal density in the registered foraminifera assemblages from the Santa Gilla Lagoon, and in some samples from the innermost part of the Cagliari Harbour, is probably due to the anthropogenic discharge of pollutants and/or fluctuating environmental parameters, as also reported in previous studies (Zampi & D'Onofrio, 1984; Frontalini et al., 2009). This compromised environmental situation has been already highlighted in an earlier paper (Zampi & d'Onofrio, 1984), which explored benthic foraminiferal distribution in six surficial sediments in the Santa Gilla Lagoon and described oligotipic assemblages dominated by *A. beccarii*, *Elphidium gunteri* Cole, 1931 and *Protelphidium anglicum* Murray, 1965, with a high abundance of abnormal specimens. The low hydrodynamic energy linked to the high concentrations of nutrients that characterise the harbour environments could explain the higher biodiversity values observed in some samples from the Cagliari Harbour (CA15, CA16, CA18 and CA24) compared with the Santa Gilla samples. These environmental conditions can cause the growth of large populations (Armynot du Châtelet et al., 2009, 2011), even if the input of large amounts of organic material can also obliterate the benthic community (Alve, 1999).

In the present investigation, it could be speculated that hydrocarbon and heavy metal pollution have a determinable effect on both population density and species' diversity in the Santa Gilla Lagoon and Cagliari Harbour stations. However, foraminiferal density and species' distribution are related to multiple inter-acting parameters (Murray, 2001), and sediment grain-size, which determines organic matter content, pollutant accumulation and oxygen concentration, is among the potential factors that influence foraminiferal composition.

CONCLUSION

The sampling stations located at Cape S. Elia and Poetto are dominated by species recognised to be characteristic of the shallow Mediterranean Sea, with sandy bottom sediments with *P. pertusus*, *R. bradyi* and *A. beccarii*. The Santa Gilla Lagoon and the Cagliari Harbour areas are characterised by a constrained or confined environment due to the restricted geographical location and intense anthropogenic activities (high levels of industrial and domestic pollution). The low abundance values and the dominance of indicative opportunistic species, such as *A. tepida*, *H. germanica* and bolivinids, are the result of these stressed conditions. The distribution patterns of these benthic foraminifera species in a polluted marine environment demonstrate that they are very sensitive and inexpensive biomarkers capable of indicating the deterioration of shallow marine environments, especially those associated with heavy metal pollution.

We have also reported an historical list of benthic foraminifera of the Cagliari Harbour (Wright, 1877). Over the past 150 years, the environment of the harbour has been subject to environmental changes. From bottom conditions characterised by sandy and vegetated sediments, with a benthic assemblage dominated by epiphytic species, we have moved to stress conditions that are probably due to anthropogenic activity and the establishment of a restricted environment, with fine sediments and opportunistic and infaunal species.

Future correlations between grain-size analysis, pollutant values and geochemical bottom sediment properties from this area will help us to better understand how such anthropogenic changes impact on foraminiferal assemblages, as well as identify the bioindicator species that can be used to define the health status of this marine and transitional environment.

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