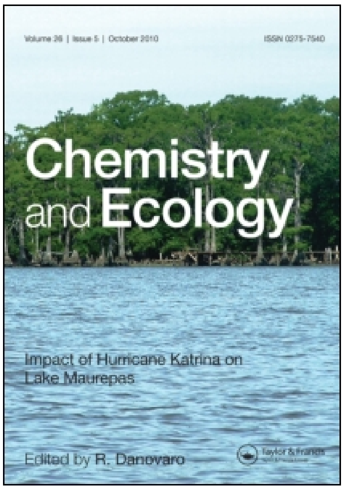

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SEDIMENT GRAIN SIZE AND ORGANIC CARBON DISTRIBUTION IN THE CABRAS LAGOON (SARDINIA, WESTERN MEDITERRANEAN)

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The aim of this work was to investigate the spatial variability of sediment bulk properties in the surface sediments as well as down-core trends, and to assess the relationship between sediment distribution and levels of total organic carbon (TOC), in the Cabras lagoon, Sardinia. Grain size distributions and TOC contents were measured in the surface sediments (0–2 cm horizon) in a grid of 31 stations. Vertical profiles along the 0–24 cm depth horizon were also measured in three stations. In the superficial horizon, TOC content was very high, up to $43\,\mathrm{mg\,g^{-1}}$, with a mean of $33\,\mathrm{mg\,g^{-1}}$. Core profiles showed a marked reduction of TOC content with depth to ~ 20–$25\,\mathrm{mg\,g^{-1}}$ and a concomitant shift in particles size towards a sandier composition (mud content decreasing from 95–100% to 70–85%) at 3–7 cm core depth. Total organic carbon contents in the uppermost layers were associated with the grain size fraction $<8\,\mu\mathrm{m}$. The results suggest that a major change in the sedimentary regime of the lagoon, associated with internal trapping and re-distribution of organic C-bounding fine particles, has been occurring in the last few decades. The cause would appear to be the construction of a dam at the lagoon mouth rising up to the high tide level in order to maintain a constant lagoonal water level.

Keywords: Sediments; Grain size; Organic matter; Coastal lagoons

1 INTRODUCTION

Over the past three decades, the accumulation of organic matter (OM) in sediments, often being a direct (*e.g.* sewage discharge, fish farming) or indirect (*e.g.* eutrophication) consequence of human activities (Nixon, 1995; Delgado *et al.*, 1999; Karakassis *et al.*, 2000; Cloern, 2001; Cancemi *et al.*, 2003), has become a major threat to coastal marine ecosystems. An excessive organic enrichment of the sediment may lead to seasonal oxygen depletion, production hydrogen sulphide and benthic macrofaunal collapse (Tsutsumi and Kikuchi, 1983; Llansó, 1991; Vismann, 1992; Diaz and Rosenberg, 1995). In sheltered areas with slow water exchange with the adjacent coastal sea, such as micro-tidal coastal lagoons, these events may rapidly affect the functioning of the whole ecosystem, which may require years for recovery (Castel *et al.*, 1996; Richardson and Jørgensen, 1996; Lardicci *et al.*, 2001; Frascari *et al.*, 2002). A thorough knowledge of the extent of

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organic enrichment of sediments and its spatial distribution is therefore of primary importance for the assessment of the environmental quality of these ecosystems.

The content of sedimentary OM is related to the sediment grain size. A higher content of OM tends to correlate with increasing mud contents due to an increasing surface area and a larger number of complexing sites in the sediment (Tyson, 1995). Higher mud contents associated with higher contents of OM may then result in a lower permeation of oxygen and a higher microbial oxygen uptake/demand (Florek and Rowe, 1983; Santschi *et al.*, 1990; Fenchel *et al.*, 1998). Hydrodynamic energy (*e.g.* tidal and/or wind-driven currents and waves) also influences the spatial distribution and transport of sediments and OM (Magni *et al.*, 2002). An area with low hydrodynamic energy will favour the accumulation of fine sediments due to enhanced settlement of silt–clay particles. By contrast, areas exposed to higher hydrodynamic energy levels will be characterised by coarser sediments (Ergin and Bodur, 1999).

Despite the fact that the relationship between sediment grain size and organic carbon is well known, an evaluation of the spatial distribution of sedimentary organic carbon at the basin scale in relation to the sediment dynamics can contribute new knowledge both to lagoon ecology and management issues.

The aim of this study was to investigate the extent and distribution of total organic carbon (TOC) contents of sediments and its relationship with grain size, both in surface sediments and along vertical core profiles, in the coastal lagoon of Cabras which is situated in the western coast of Sardinia (western Mediterranean).

A parallel study investigated the effect of sediment characteristics on the structure and distribution of macrofaunal communities in Cabras lagoon (Magni *et al.*, 2004).

2 STUDY SITE

Cabras lagoon is a shallow water body (mean depth 1.7 m) located on the west coast of Sardinia, western Mediterranean sea (39°57′ N, 008°29′ E; Fig. 1), and is one of the largest brackish water basins in the Mediterranean region with a surface of 22 km^2. The lagoon has a high economic rating due to extensive fishery activities (*e.g. Liza ramada, Mugil cephalus*) involving about 300 people. The northern part of the lagoon is connected to a small river which represents the major source of freshwater. River discharge is rather limited due to a low rainfall regime in the region (ca. 10–100 mm from July–December, respectively, Pinna, 1989) and an increasing water demand for land use, especially agriculture. Although there is a trend towards increasing salinity caused by a progressive reduction of freshwater input, salinity may drop to $<$10 PSU during rainfall periods and raise up to $>$30 PSU, especially in summer. In the southern part of the basin, there is a wide artificial channel dredged in the late 70s which is separated from the adjacent gulf by a low dam rising up to the high-tide level to allow the flushing of excess water in case of flood. A net of small secondary creeks flowing together into the main channels partially connect the mouth of the lagoon to the Gulf of Oristano. The tidal amplitude is $<$40 cm. As such water exchange between the lagoon and the coastal systems is very limited.

A dystrophic event caused a massive fish mortality in summer 1999, probably due to the decay of a surplus of sedimentary OM and the release of high levels of hydrogen sulphide from the sediments (IMC, 1999).

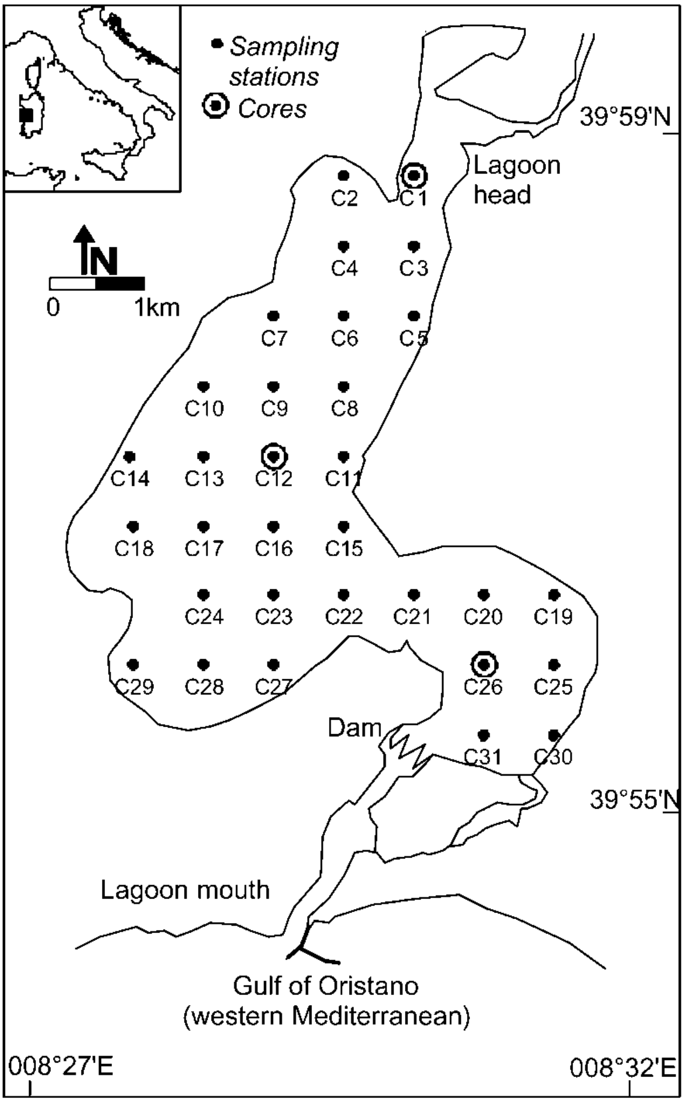

FIGURE 1 Study area and location of the sampling stations in Cabras lagoon (western Mediterranean). ◉ indicate stations where vertical profiles of TOC and sediment grain size were determined.

3 MATERIAL AND METHODS

3.1 Sampling and Analysis

Thirty-one stations were selected on a regular square grid, each station spaced at 750 m, covering the whole lagoon (Fig. 1). Sampling campaigns were conducted on four dates between the end of April and the beginning of May 2001. At each station, duplicate sediment samples were collected using a manual corer (40 cm long, 10 cm diameter) penetrating at least 25 cm into the sediments. Additional cores were collected to measure the redox potential (Eh) using a Crison Eh-meter 507 with a redox platinum electrode. Water depth was simultaneously measured using a calibrated staff.

Sediment cores collected for grain size, organic carbon and OM analyses were frozen (−21 °C) before being stored. Subsequently, the surface (0–2 cm) layer of each core sample was carefully sliced off the frozen core to sub-sample the core superficial section. At three stations (C1, C12 and C26, Fig. 1) duplicate cores were sliced at 2 cm intervals and analysed along a 24 cm horizon, at 2 cm intervals. Sediments from the same layer were mixed together and treated as one single sample. Samples were dried at 50 °C for 24 h and the water content (WC) was determined as a loss of weight. Total organic carbon was determined using a Fisons CHN analyser following the procedure described by Froelich (1980) modified by Hedges and Stern (1984). The OM content in the sediments was determined from a sub-sample (ca. 1 g) by loss on ignition (LOI) at 500 °C for 3 h (Dean, 1974).

A sub-sample of ca. 4 g was used for the grain size analysis. This subsample was suspended on a large volume (500 ml) of distilled water in order to desalinate sediments, treated with hydrogen peroxide (H_2O_2) in order to eliminate OM and wet sieved through a 63 µm net. The sandy fraction (>63 µm) remaining in the sieve was dried and weighed. The suspension with the muddy fraction passing through the 63 µm sieve was diluted up to obtain a sediment concentration $\approx$0.5 mg ml^{-1} and to further reduce the salt concentration. Ten milliliter of diluted suspension were treated with Na-Hexametaphosphate 0.6% to avoid particle flocculation. The grain size analysis of the fraction <63 µm was performed using a laser Galai CIS 1 instrument, with specific analytical size intervals of 0.5 µm (Molinaroli *et al.*, 2000).

3.2 Sediment Classification and Statistical Analysis

Sediments were classified using the texture classification of gravel-free muddy sediments on ternary diagrams proposed by Flemming (2000). The silt–clay boundary was taken at 4 µm rather than at 2 µm. This choice was driven by the instruments used for grain size analysis. It is known that laser systems have a bias in comparison with analytical methods based on the time of sedimentation (*e.g.* Sedigraph or pipette) with a tendency of shifting finer size classes toward the coarser fractions (Vanderberghe *et al.*, 1997; Molinaroli *et al.*, 2000). For example an analysis of the same sample with a Galai laser system and with a Sedigraph has shown that the fraction <4 µm of the former corresponded to the percentage <2 µm of the latter (Molinaroli *et al.*, 2000).

A Q-mode factor analysis was applied in order to assess the relationships between grain size (expressed at 1 phi intervals), WC, and TOC. One fundamental drawback in the factor analysis is that grain size data, expressed as percentages with a constant sum, are not free to vary independently and it is inevitable that induced correlation will arise (Syvitski, 1991). To avoid this problem, data were ranked to obtain comparable units of variables. Factor analysis was performed to find the directions of maximum variance of data (Le Maitre, 1982; Swan and Sandilands, 1995). Ranks of data values were used as input data matrix whereas Principal Component analysis was used as extraction method, factor being normalized by orthogonal rotation according to the VARIMAX procedure.

3 RESULTS

3.1 Surface Sediments

The surface sediments of the lagoon are mainly silty–clayey (silt + clay mean content 89% of the dry weight) with a high content of OM (10%) and TOC (33 mg g^{-1}) and negative Eh values (−109 mV) (Tab. I).

TABLE I Mean Values of Sedimentary Variables of Surface Sediment Samples. The Mean Depth of the 31 Sampling Stations is also Reported.

Surface sediments (0–2 cm)	*Median*	*Mean*	*sd*	*n*	*Range*
Depth (m)	1.8	1.7	0.2	31	1.2–2.1
Water content (%)	80.0	77.8	7.5	31	48.9–85.0
LOI (%)	11.2	10.5	2.4	31	3.5–14.3
TOC (mg g^{-1})	34.1	32.8	7.2	31	9.6–42.9
Eh (mV)	−97	−109	56	12	−30/−220
Sand (%)	3.0	10.8	18.1	31	0.4–72.8
Silt (%)	48.3	46.6	11.2	31	11.7–65.3
Clay (%)	45.2	42.6	9.5	31	15.5–56.6
Silt/clay	1.1	1.1	0.3	31	0.7–2.1

The ternary plot representation of the sand/silt/clay ratios (Fig. 2a) highlights that 21 out of 31 surface samples have a mud content higher then 95%, silt/clay ratio ranging from 0.7 to 2.1 with a mean value of 1.1 (Tab. I). In the ternary plot of Figure 2b the fine-grained sediment fraction are represented by the <8 µm and the 8–63 µm fractions. The <8 µm fraction is known as the 'sortable' silt fraction (McCave *et al.*, 1995) mainly consisting of single particles and an aggregated or flocculated fraction mainly comprising particles finer than 8–10 µm (McCave *et al.*, 1995), whereas the 8–63 µm fraction may be considered as not aggregated silt particles. The position of samples in the ternary plot of Figure 2b highlights that the samples are mainly composed by the <8 µm fraction.

Silt/clay ratio values shows a clear pattern, values decreasing from south to north (Fig. 3a). Sediments are characterised by the dominance of silt in the southern area (silt/clay > 1.1), whereas the clay content increases towards the central-northern sector of the lagoon (silt/clay <0.9).

The distribution pattern of the ratio between the >8 µm and <8 µm fractions is reported in Figure 3b. Low values indicate a dominance of sortable silt fraction occurring in the inner sector of the lagoon and in proximity of the lagoon mouth.

The TOC content ranges from 9.6 to 42.9 mg g^{-1} (Tab. I). However, most samples (27 out of 31) have TOC contents higher then 30 mg g^{-1}, indicating high values of organic carbon content in surface sediments. The spatial distribution of TOC is illustrated in Figure 4.

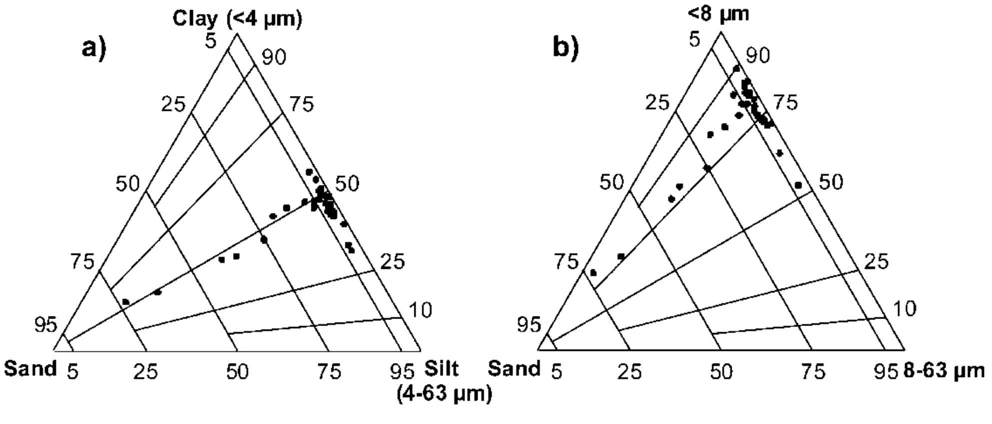

FIGURE 2 Ternary diagrams of surface (0–2 cm) sediments based on the sand/silt/clay ratio (a) and sand/8–63 µm/<8 µm ratio (b). The boundaries inside the diagrams delimiting the different sediment types are those proposed by Flemming (2000).

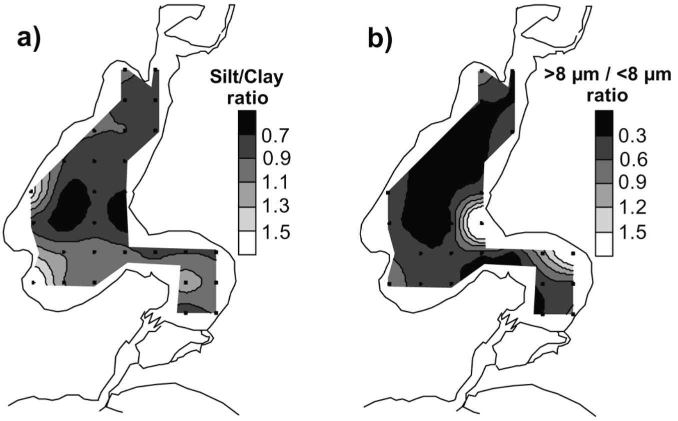

FIGURE 3 Silt/clay ratio (a) and (>8 µm)/(<8 µm) ratio (b) in surface sediments of the Cabras lagoon.

Values up to 43 mg g^{-1} occur in the inner part of the lagoon. High TOC values are also found in the southernmost part, close to the lagoon mouth, while TOC values generally decrease toward the shorelines as the sediment gets coarser (Fig. 4). The spatial distribution of TOC shows a pattern similar to the distribution of the <8 µm/>8 µm ratio reported in Figure 3b. This relationship indicates that higher TOC values are associated to sediments with a high percentage of sortable silt fraction.

The relationships between sediment texture, TOC, and water content were investigated in more detail using a Q-mode factor analysis. Two factors were extracted which together explain 67.8% of the total variance (Tab. II). The first factor (47.4% of the variance) is positively correlated to the finer grain size classes (<8 µm), TOC and WC and negatively correlated to the sand content (>62 µm). The second factor (20.4% of the total variance) is correlated to the medium and coarse silt particles (8–32 µm).

Spatial distributions of the score values obtained for the first and second factors were generated using a contour interpolation (Fig. 5a and b). Figure 5a shows that factor 1 increases towards the central-inner part of the lagoon and the south, close to the lagoon mouth, suggesting the occurrence of higher TOC contents and fine sediments in those

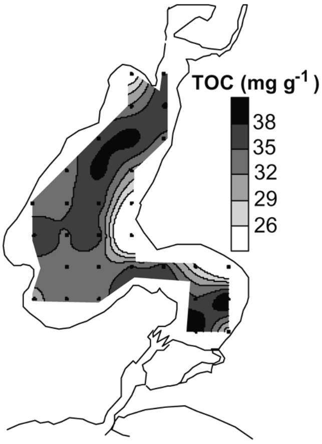

FIGURE 4 Total organic carbon in surface sediments of the Cabras lagoon.

TABLE II Correlation Between Factors and Measured Variables and Explained Variance for Factor Analysis of Surface Sediments. Bold Variables are Significant ($p < 0.001$).

Variables	*Factor 1*	*Factor 2*
TOC ($mg\,g^{-1}$)	**0.76**	0.20
Water content (%)	**0.84**	0.35
<2 μm	**0.67**	−0.20
2–4 μm	**0.89**	−0.19
4–8 μm	**0.86**	−0.06
8–16 μm	0.34	**0.72**
16–32 μm	−0.12	**0.89**
32–64 μm	−0.46	0.42
>62	**−0.82**	−0.35
Explained variance	47.4%	20.4%
Cumulative explained variance	47.4%	**67.8%**

areas (Fig. 5a). By contrast, factor 1 score values decrease toward the shores where the sediments became sandier. Factor 2 increases towards the southern sector (Fig. 5b) and highlights a grain size gradient from north to south, sediments becoming more silty in this direction.

3.2 Sediment Cores

Vertical changes of TOC and mud content along sediment cores collected at three stations (C1, C12 and C26, in the northern, central and southern sector, respectively) are illustrated in Figure 6a. The TOC values show a marked decrease with depth at all three stations, varying from 35–38 $mg\,g^{-1}$ in the superficial layers to 20–25 $mg\,g^{-1}$ in the deeper sections. A discontinuity level is apparent in all three cores, its depth increasing from 3 cm in the northern (C1), to 5 cm in the centre (C12), and 7 cm in the south (C26) respectively (Fig. 6a).

The grain size composition shows a similar and mostly parallel trend. The mud content also decreases with depth from 95–100% in the surface layers to 70–85% in the deepest layer with a marked drop in correspondence to the TOC discontinuity level at each station. Total organic carbon and mud contents along the vertical sediment profile are thus positively correlated ($R = 0.61$, $p < 0.001$).

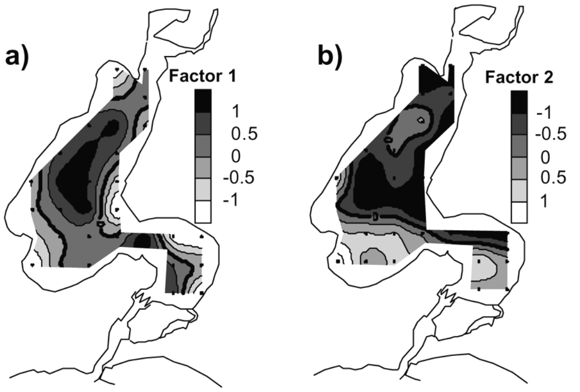

FIGURE 5 Variability of the Factor 1 (a) and Factor 2 (b) scores as resulting from factor analysis of surface sediments. The weights of the variables are reported in Table II.

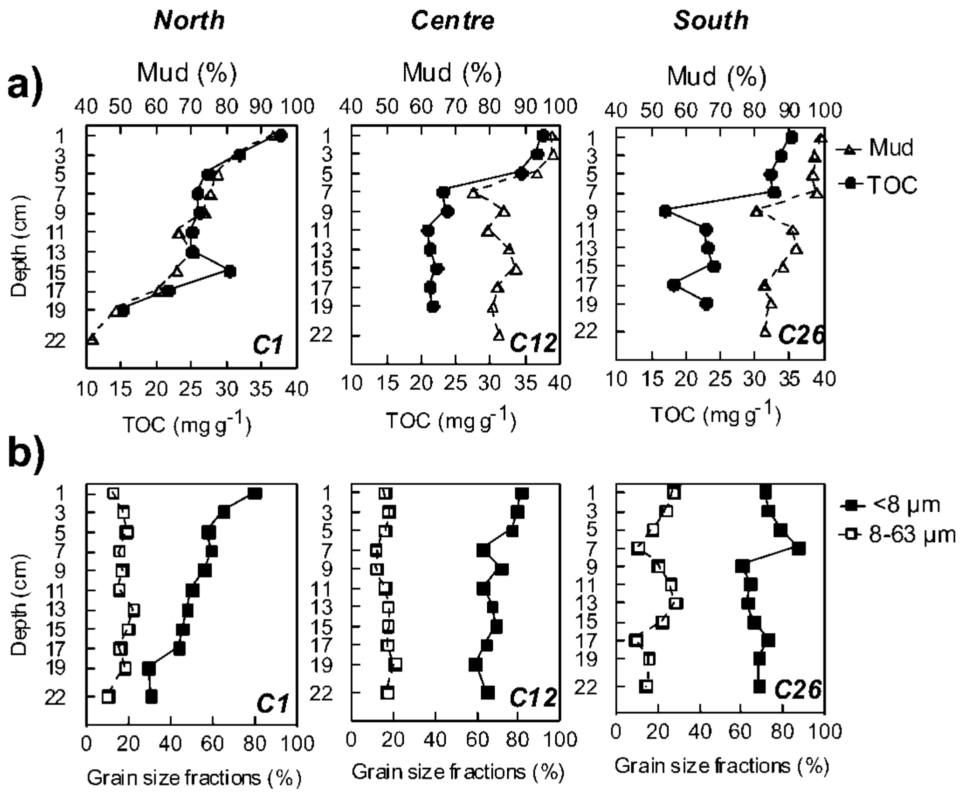

FIGURE 6 (a) Trend of TOC and mud content and (b) trend of <8 µm and 8–63 µm grain size fractions with depth through three core profiles.

The analysis of depth variations of grain size classes within the mud shows a decrease of the fraction <8 µm, having the same discontinuity levels as those described above (Fig. 6a and b). By contrast, the fraction 8–63 µm does not show a clear trend with depth. The variation with depth of mud content is thus related to an increase in the upper layer of the sortable silt fraction. This finding is evidenced by the linear correlation between mud content and the sortable silt fraction ($R = 0.93$, $p < 0.001$), while the mud and 8–63 µm fraction are not correlated.

4 DISCUSSION

In coastal lagoons, TOC and OM levels are generally higher than those found in coastal marine environments (Tyson, 1995), although coastal sites heavily affected by human activities, such as sea farm sediments, may also have very high OM contents, up to 24% (Delgado *et al.*, 1999; Cancemi *et al.*, 2003). The levels of TOC and OM in the surface sediments of the Cabras lagoon are much higher than those in other Mediterranean lagoons. For example the sediments of the nearby S'Ena Arrubia lagoon have OM values mostly within 2% (De Falco and Guerzoni, 1995). Values of ~0.2–7% are reported for the Etang de Vendres lagoon in southern France (Aloisi and Gadel, 1992). More similar values are found in other Mediterranean lagoons over-enriched by OM, such as Spavola and Fattibello lagoons in the North Adriatic (Frascari *et al.*, 2002) and the Orbetello lagoon in the Thyrrenian sea (Lenzi *et al.*, 1997; Lardicci *et al.*, 2001).

The spatial distribution of TOC in Cabras lagoon shows that values $>32\,\mathrm{mg\,g^{-1}}$ occur in about 50% of the lagoon bed surface, indicating an overall organic enrichment of the lagoonal sediments. The TOC distribution pattern, however, cannot be related to a punctual external source of OM input. In fact, the highest concentrations of TOC are found in the inner sector of the lagoon.

The TOC distribution in surface sediments is clearly related to the grain size composition of the sediments. As revealed by factor analysis, the grain size partitioning in the surface sediments shows two trends. The first trend (factor 1) can be considered to be controlled by a combination of hydrodynamic energy and lagoonal morphology: finer sediments are removed from the nearshore areas to be deposited in the deeper parts. By contrast, the second trend (factor 2) appears to be related to the hydrodynamic energy alone. Sediment grain size changes from coarser in the south, a relative higher energy area, to finer in the north, a lower energy area as indicated by the clay content. The factor 2 score distribution shows a pattern similar to the silt/clay ratio which is known to have hydrodynamic significance (Ergin and Bodur, 1999; Flemming, 2000).

This sedimentary pattern can thus be explained by the interaction of currents and waves. Wind and waves have indeed been demonstrated as one of the main factors which force sediment transport in micro-tidal coastal lagoons (*e.g.* Isla, 1995). In our study area, the dominant wind direction is NW (*Mistral*, Pinna, 1989), and the more exposed areas are consequently those in the south and along the eastern shores. In areas characterised by higher energy, the action of wind-induced waves cause sediment re-suspension with a resulting transport of finer particles and associated OM towards the inner and deeper lower energy sectors of the lagoon.

As shown by factor analysis, TOC is associated with the finer sediment particles, *i.e.* $<8\,\mu\mathrm{m}$ sediment fraction, as a result of which it is associated the sector of fine sediment deposition. Correlation between TOC and granulometry is commonly evaluated by comparing TOC contents *vs.* mud contents (Tyson, 1995). In Cabras lagoon the spatial variability of TOC in the surface sediments, although quite homogeneously muddy, can be explained in terms of grain size fractionation within the muds.

The analysis of sediment core profiles suggests a recent change in the environmental condition of the lagoon over the past few decades.

The exchange of water between the lagoon and the sea, in particular, has been severely affected by the construction, at the end of 70 years, of an artificial channel closed by a dam (Fig. 1) rising up to the high-tide level with the aim of maintaining a constant water level in the lagoon while allowing excess flood waters to be flushed. This dam favours the trapping of fine sediments inside the lagoon. Furthermore the fresh water input at the lagoon head has been reduced in the past 20 years, following the increase of water use for agriculture.

We infer that these changes have reduced the internal hydrodynamic energy then favouring the deposition of mud and, in particular of the sortable silt fraction (McCave, 1995) as shown by the core profiles.

The TOC contents are correlated to the $<8\,\mu\mathrm{m}$ grain size fraction, both increasing in the upper layers. This trend may be explained by the reduction of internal hydrodynamic energy capable of oxidising the particulate organic matter settled on the lagoon bed, even though a recently increase of organic matter input can not be excluded. Further data concerning core dating, not available in this study, will also be helpful to interpret the environmental changes occurred in Cabras lagoon.

In conclusion, this study highlights that the spatial variability of sedimentary organic carbon in Cabras lagoon is tightly related to sediment grain size, in particular to the sortable silt fraction.

Sediment characteristics varied from the deeper to the superficial horizons, with an increase of the <8 μm fraction and organic carbon contents due to the variation of hydrodynamic conditions as consequence of the modification of the lagoon mouth. These sediment conditions were probably one of the triggering causes of the massive fish mortality that occurred in June 1999 following the release of toxic acid volatile sulphide from sediments to the water column (IMC, 1999).

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