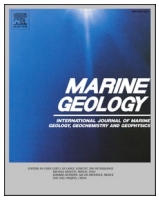
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Research Article

A new sediment map for the western side of the Central and Southern Adriatic Sea based on sedimentology, geochemistry and biogeochemistry

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ABSTRACT

This work discusses the sedimentological and biogeochemical features of the Central and Southern Adriatic Sea's surface sediment. A total of 107 samples from the cruise PERTRE2016 were analyzed for sediment grain size, major and trace elements, LOI, and total and organic carbon. The aim was to identify sedimentary facies based on geochemical and biogeochemical features and their spatial distribution. This includes recognizing regional patterns of sediment dispersal, geochemical signals for provenance, and local features. Q-mode factor analysis of grain size, geochemical and biochemical properties of surface and subsurface sediments was used to identify sedimentary facies.

The statistical processing of sediment properties made it possible to identify five factors that can be interpreted as distinct sedimentological and biogeochemical facies. The characterization and distribution of these facies enabled a more comprehensive understanding of the current hydrodynamic, sedimentological, geochemical, and biogeochemical processes occurring in the Central and Southern Adriatic Sea, as well as the identification of the primary sediment source areas.

1. Introduction

Marine sediments result from different processes and factors. Their features are influenced by sediment source, current transportation and sedimentation, wave motion resuspension and reworking, as well as primary production and biological activity occurring in both the water column and the bottom sediments (Berner, 1980; Fralick and Kronberg, 1997; Chester, 2000; Hammond et al., 2004; Schulz and Zabel, 2006; Burdige, 2007; Seibold and Berger, 2017a, 2017b). Among the most important properties of marine sediments controlled by these factors are the grain-size, and the geochemical, mineralogical, and petrographic composition (Burdige, 2007).

Moreover, the residence time and pathways of solid particles, along with their chemical and physical alteration in the water column and in the sediments, particularly during the early stages of diagenesis, are key factors that can influence sediment mineralogy and geochemistry (Berner, 1980). Early diagenesis primarily results from the mineralization of organic matter, mediated by macro, meio, and microbial activities, which establishes different redox and pH conditions within the sedimentary environment. This can affect the geochemical behavior of certain elements and compounds as a result of oxidation, reduction, precipitation, and dissolution reactions, leading to changes in the biogeochemical and mineralogical properties of sediments (Berner, 1980; Spagnoli and Bergamini, 1997; Spagnoli and Ravaioli, 2023).

Sediments record provenance signals, diagenetic processes, past depositional environments, natural anomalies, pollution events, therefore, sediment geochemistry can be used to reconstruct the history of inputs, hydrography, and ecosystem changes within a basin.

Various studies have been carried out on the sedimentological, geochemical, and biogeochemical properties of superficial sediments of the Western Adriatic Sea to infer present and past depositional processes, provenance areas, general Adriatic circulation, and anthropogenic impacts. Studies regarding geochemical, mineralogical, and petrographic compositions aimed at recognizing sources, transport processes, and petrographic provinces have been carried out by Pigorini (1968), Dinelli and Lucchini (1999), Marcaccio et al. (2003), Spagnoli

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et al. (2008), Goudeau et al. (2013), Spagnoli et al. (2014), and Amorosi et al. (2002, 2022). Other studies have focused on bottom sediment grain-size, highlighting the control of transport and reworking processes (Wang and Pinardi, 2002; Frascari et al., 2006; Miserocchi et al., 2007; Paladini de Mendoza et al., 2023) or on benthic communities as a results of particle dynamics influenced by the primary production, grazing, fecal pellet productions, and exudation (Mauri et al., 2004; Focardi et al., 2009; Fossile et al., 2021; Rostami et al., 2021, 2023). Additionally, studies discussing anthropic signals are also present (Frascari et al., 2000; Annibaldi et al., 2009; Spagnoli et al., 2010, 2021; Romano et al., 2013; Pérez-Albaladejo et al., 2016; Droghini et al., 2019; Frapiccini et al., 2024; Fanelli et al., 2025).

The objective of this study was to identify the coupling and spatial relationships between biogeochemical and grain-size variables to determine sedimentary facies resulting from common depositional processes and sediment sources. These associative and spatial relationships enabled us to reconstruct the current depositional processes and to identify the sediment provenances. Moreover, the identification of these sedimentary facies also provides an indispensable basis for interpreting current, future, and past changes of both natural and anthropogenic origin, in particular as regards to local or global anthropogenic impacts.

To achieve these aims, we analyzed geochemical element concentrations (both major and trace elements), grain-size (sand, silt, and clay fractions), as well as total and organic carbon contents in surface sediments collected fron the Italian sector of the Central and Southern Adriatic Sea.

2. Study area

2.1. Geomorphological setting and physiography of the Adriatic Sea

The Adriatic Sea is a semi-enclosed, elongated basin extending in the NW-SE direction for about 800 km between the Italian and Balkan peninsulas (Fig. 1).

The Adriatic Sea may be divided into three main sectors (Colantoni, 1990, Fig. 1): i) the Northern Adriatic, between the Gulf of Trieste and the line between Ancona and Pag Island; ii) the Central Adriatic Sea, from the above-mentioned line and the Gargano Promontory-Lagosta line; iii) the Southern Adriatic Sea sector, which extends from the Gargano-Lagosta line to the Otranto Strait.

The Northern and Central Adriatic are characterized by a large and shallow continental shelf with the seabed weakly sloping (0.4 ‰) up to the maximum depth of 120 m. South of the 120-m depth, the Central Adriatic is characterized by higher depths in the Mid-Adriatic Depression (MAD), also called the Pomo Pit or Jabuka Pit, and in the Gallignani Sill. The MAD is an important morphological feature of the basin, which starts at the 120 m shelf break and extends from Pescara to Sibenik, at depths of 120–130 m. The MAD includes three minor basins reaching a maximum depth of about 260 m, 270 m, and 240 m, respectively. These three depressions are aligned in the NE-SW direction, perpendicularly to the axis of the basin and to the Apennine structure orientation (Argnani, 2018). Northeastward, the MAD closes abruptly, and instead rises with a regular ramp, towards the south-east. The Gallignani Sill area, situated

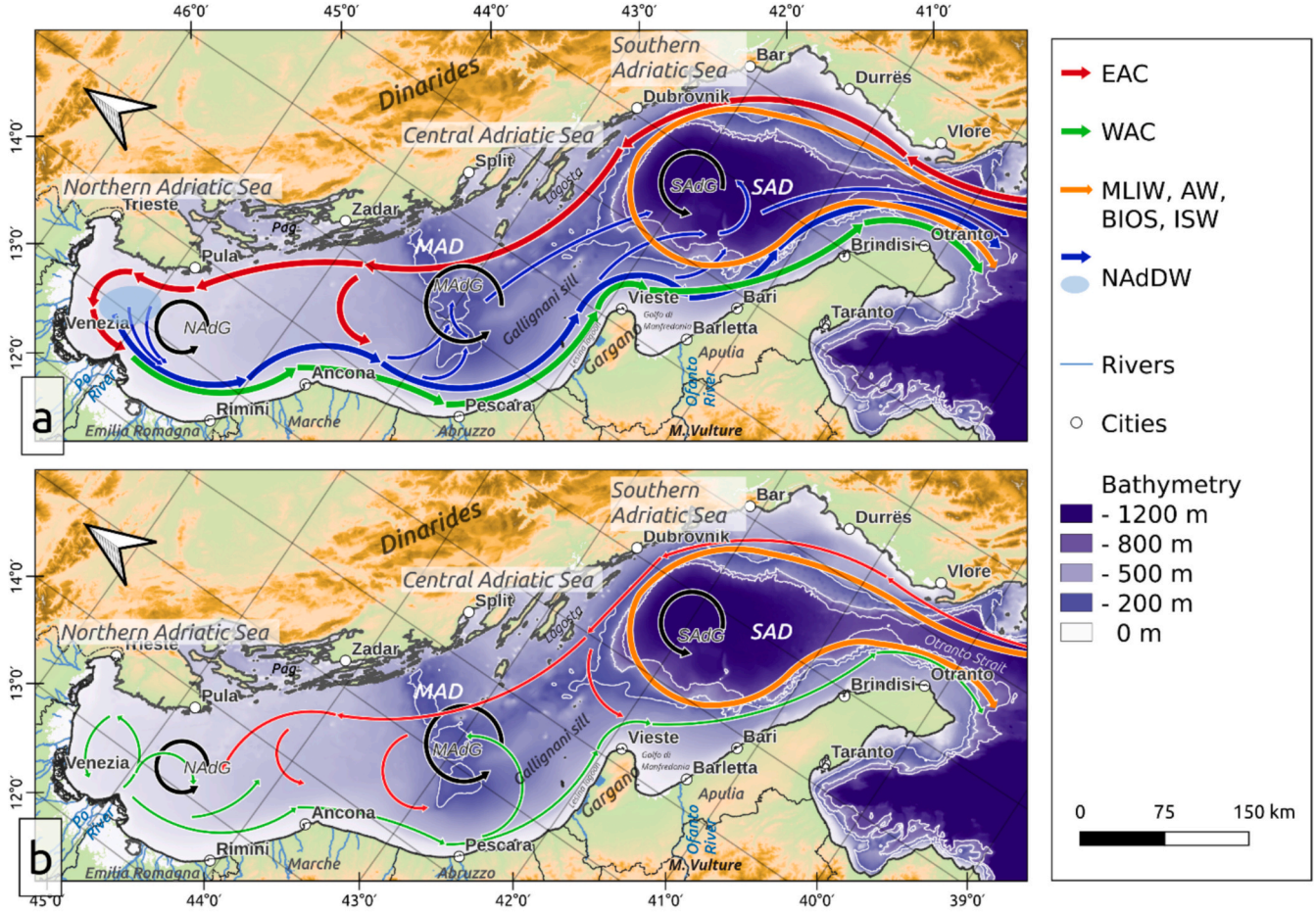


Fig. 1. Physiographic division and circulation of the Adriatic Sea (from Spagnoli et al., 2021 and Umgiesser et al., 2022, modified). a) summer circulation, b) winter circulation (bathymetry data from https://www.gebco.net/). EAC: Eastern Adriatic Current; WAC: Western Adriatic Current; NAdDW: North Adriatic Dense Water; MLIW: Modified Levantine Intermediate Waters; AW (Atlantic Waters); BiOS (Bimodal Oscillation System, MLIW or AW); NAdG: North Adriatic Gyre; MAdG: Mid-Adriatic Gyre; SAdG: South Adriatic Gyre. MAD: Mid-Adriatic Depression; SAD: South Adriatic Depression.

south of the MAD, is characterized by irregular high and low morphologic features that trend southeast and east.

The Southern Adriatic is characterized by a sub-circular deep basin, which stretches towards the Otranto Strait with a maximum depth of about 1230 m, the Southern Adriatic Depression (SAD). On the west, the SAD is bordered by a shelf that gently and irregularly dips eastward. This shelf reaches depths of about 200 m depth in the northern sector and narrows as it extends southward, where a noticeable shelf break occurs at a depth of approximately 150 m. The southern limit of the Adriatic Sea is defined by the Otranto Sill, located at a depth of 800 m, where the sea transitions into the Ionian Sea.

2.2. Oceanographic features of the Adriatic Sea

The hydrography of the Adriatic Sea is controlled by three main forces: i) rivers, which contribute solid loads, dissolved chemicals, and freshwater inputs, mainly occurring in the western sector of the basin, leading to heat loss and a decrease in salinity; ii) wind action, which produces strong heat exchanges on the water surface, storms affecting the bottom sediments by resuspension, and seasonal changes in circulation; and iii) seawater entering from the Otranto Strait, which carries warm and high-salinity water masses inside the basin (Artegiani et al., 1997; Umgiesser et al., 2022).

The general hydrodynamic regime of the Adriatic Sea (Fig. 1) is dominated by a cyclonic circulation driven by thermohaline currents. This regime features seasonally modulated cyclonic gyres and a microtidal system (Orlic et al., 1992; Artegiani et al., 1997). Seawater enters the Adriatic Sea through the eastern side of the Otranto Strait, where a variable and complex circulation occurs, driven by the Adriatic-Ionian Bimodal Oscillating System, or BiOS (Gačić et al., 2014). Along the eastern side of the Otranto Strait two main water masses enter: the superficial waters from the Ionian Sea (ISW) and at greater depth, between 200 and 600 m, the Modified Levantine Intermediate Waters, coming from the Eastern Mediterranean (MLIW) or the Atlantic (AW).

Into the Adriatic, the currents are directed northward along the eastern coast (Eastern Adriatic Current: EAC) and southward close to the Italian coast (Western Adriatic Current: WAC). The global cyclonic circulation is divided into three sub-circulation cells (Fig. 1) in the Northern, Central, and Southern sectors of the Adriatic Sea, induced by winds, and controlled by bathymetry (Orlic et al., 1992; Artegiani et al., 1997).

Circulation in the Adriatic Sea exhibits seasonal variation. In winter, three sub-cells characterized by cyclonic circulation prevail, dividing the Adriatic into three hydrodynamic domains: the Northern, Central, and Southern sectors (Fig. 1). In summer, the cyclonic current weakens, leading to the formation of small scale eddies (Artegiani et al., 1997; Gačić et al., 1999). Additionally, a strong stratification of the water column occurs, which generates hypoxic or anoxic pockets near the bottom, particularly in the southeastern region of the Po River Delta (Alvisi et al., 2013).

In this general setup, the formation and movement of a dense water mass is also present in the Adriatic Sea: the North Adriatic Dense Waters (NAdDW). NAdDW is a cold and high-salinity water mass forming in winter in the Northern Adriatic Sea when the Bora wind blows (Boldrin et al., 2009; Vilibic et al., 2016). The NAdDW accumulates at the bottom sea of the North Adriatic Sea and typically flows southward close to the western Italian coast during spring. It partially disperses into the MAD and partially flows further south (Fig. 1), occurring annually or biennially (Marini et al., 2016).

2.3. Geological setting

From a geological prospective, the Adriatic Basin formed as a result of the collision between the African and Eurasian plates. In this context, the Apennine thrust belt overrides the foredeep of the Adria microplate, which is primarily filled with sediments that have weathered from the Apennine and the Alps (van Hinsbergen et al., 2020).

Present sedimentological processes in the Adriatic Sea are strongly influenced by factors such as water depth, the morphology of the seafloor, summer and winter hydrographic circulation patterns, wave motion, and the composition of sediments and rocks in the source areas (Spagnoli et al., 2014). The interactions among these factors promote sediment fluxes that exhibit primarily longitudinal dispersion, with a lesser degree of offshore spread of finer particles (Tomadin, 2000). These particles are deposited on the partially reworked sediments of earlier alluvial plains, lagoons, beaches, and other relict substrates (Colantoni and Gallignani, 1978; Ferretti et al., 1986; Ridente, 2018), corresponding to the last sea level rise (about 120 m in the last 20,000 years).

As a result of these present and past interactions, the bottom of the Adriatic Sea shows a Holocene accretion sediment wedge that extends continuously from the Adige River to the Apulia coast south of Bari (Savelli et al., 1990; Cattaneo et al., 2007; Maselli et al., 2011). This sediment wedge consists of a subparallel and confined belt, close to the Italian coastline, primarily formed by the WAC, which restricts the offshore drift of sediment particles. This belt consists of a coastal sandy prism up to a depth of around 6–8 m (i.e., the wave closure depth), which evolves offshore to finer sediments at higher depths for the reduced control of storm and wave motion control. In the northern sector of the Adriatic Sea, the fine sediments partially mix with the outcropping, older, and, generally, coarser sediments belonging to relict morphologies following the last sea level rise (Trincardi et al., 1996). In the Central Adriatic Sea sector, the Holocene wedge is continuous and composed of fine sediments up to the MAD (Curzi and Tomadin, 1987), while in the Southern Adriatic Sea, the wedge closes on the coast south of Bari and exhibits sediment grain-size, thickness and shape irregularities (Ridente, 2018).

The composition of the sediments of the Holocene wedge (mineralogy and geochemistry) reflects the lithological and compositional characteristics of their provenance areas (Spagnoli et al., 2008, 2010, 2014).

2.4. Present continental inputs and oceanographical dynamics

Generally, four main regions can be traced, which correspond to particular drainage areas: i) the eastern Alps; ii) the Po Basin; iii) the basins of the Apennine rivers to the north of the Gargano Promontory; and iv) the basins of the Apennine rivers to the south of the Gargano Promontory (Pigorini, 1968; Curzi and Tomadin, 1987; Tomadin, 2000; Cattaneo et al., 2003; Spagnoli et al., 2010; Spagnoli et al., 2014; Amorosi et al., 2022). North of the Po River, a carbonate composition prevails (Ravaioli et al., 2003). South of this river, the solid inputs are composed of terrigenous sediments with varying amounts of carbonates (Ravaioli et al., 2003; Spagnoli et al., 2014). Here, two major sediment fluxes can be recognized (Spagnoli et al., 2014; Cattaneo et al., 2003): i) the “Apennine flux”, near the coast; and ii) the “Po River flux”, located offshore, which carries the sediments supplied by the Po River along the basin. A minor sediment flux in the Southern Adriatic is associated with the rivers flowing on the eastern (non-Italian) side, especially the Albanian rivers (Dinelli and Lucchini, 1999).

The rivers that flow on the Adriatic western side primarily transport the most recent solid load. The particle contribution from the Northern and Western Adriatic Sea rivers is represented primarily by the solid load of the Po River (Frignani et al., 2005; Syvitski and Kettner, 2007) and, secondarily, by the solid inputs of the Italian minor rivers (Cattaneo et al., 2003).

The Southern Adriatic Sea is characterized by two physiographic areas: the shelf area and the basin area. Here, carbonates and marls of pelagic environment (Ricchetti et al., 1988), as well as finer contributions from the northern and eastern source areas, are present (Colantoni and Gallignani, 1978; Ridente, 2018; Amorosi et al., 2022).

The sediments transported by WAC along the southeast offshore shelf

of the Gargano Promontory generate a subaqueous delta. This formation results from the interaction of various factors, including the morphological features of the Gargano Promontory, hydrodynamic patterns, and the dispersion of sediments parallel to the shore (Cattaneo et al., 2003; Spagnoli et al., 2008). In this sector, continental inputs are mainly due to the Ofanto River, the largest river flowing into the south Adriatic Sea, while other minor rivers (Carapelle, Cervaro and Candelaro) display a seasonal and limited contribution to the sediment supply (Milliman et al., 2016; Verri et al., 2024).

3. Materials and methods

3.1. Sampling

Sediment samples were collected in the western area of the Central and Southern Adriatic Sea, from Ancona to Santa Maria di Leuca (Fig. 2), during the PERTRE cruise, which was carried out on board the R/V *G. Dallaporta* from the 16th of September to the 4th of October 2016.

The sampling network consisted of transects perpendicular to the Italian coast and spaced about 35–40 km. A total of 107 surface and core sediment samples were collected by a box corer (width 20.5 cm, depth 29.5 cm, height 49.5 cm).

On board, immediately after the recovery, the sediments were:

- Described in terms of macroscopic characteristics, i.e., colour (using the Munsell chart), granulometry, lateral and vertical sedimentary structures, and biological features;
- Characterized by measuring the pH and redox potential (Eh) with punch-in electrodes;
- Sub-sampled from the superficial 0–5 cm interval using a plastic spatula which was then divided into aliquots for laboratory analyses;
- Sub-sampled using a PVC liner to collect an undisturbed core for further analyses.

Sediments for grain-size and water content analyses were placed in polyethylene jars and stored at 4 °C until analysis. Sediment for biogeochemical analyses were stored at −20 °C in polyethylene jars. Superficial sediments were analyzed in the laboratory for water content, granulometric composition, geochemistry, and total carbon (TC) and organic carbon (TOC).

3.2. Analytical methods

Water content was gravimetrically determined after heating at 70 °C until constant weight of an aliquot of the sampled sediment. Porosity was calculated using the formula by Berner (1971).

Sediment grain-size analyses were conducted through wet sieving and X-ray sedigraphy analyses (details on the methods are reported in Fanelli et al., 2025), with sediment samples classified according to Shepard (1954).

Biogeochemical analyses were carried out on freeze-dried sediment samples stored at −20 °C. Geochemical analyses were carried out by X-ray fluorescence (XRF) spectrometry. XRF enabled the identification of major element concentrations (SiO_2, Al_2O_3, TiO_2, Fe_2O_3, MnO, CaO, MgO, K_2O, Na_2O, and P_2O_5), as well as trace elements (Sc, V, Cr, Co, Ni, Cu, Zn, As, Rb, Sr, Y, Zr, Nb, Ba, Ce, Pb, and Th). The elements were analyzed using pressed powder pellets, following the methods outlined by Franzini et al. (1972), Leoni and Saitta (1976), and Leoni et al. (1982) for matrix correction. This analysis was conducted with a Panalytical

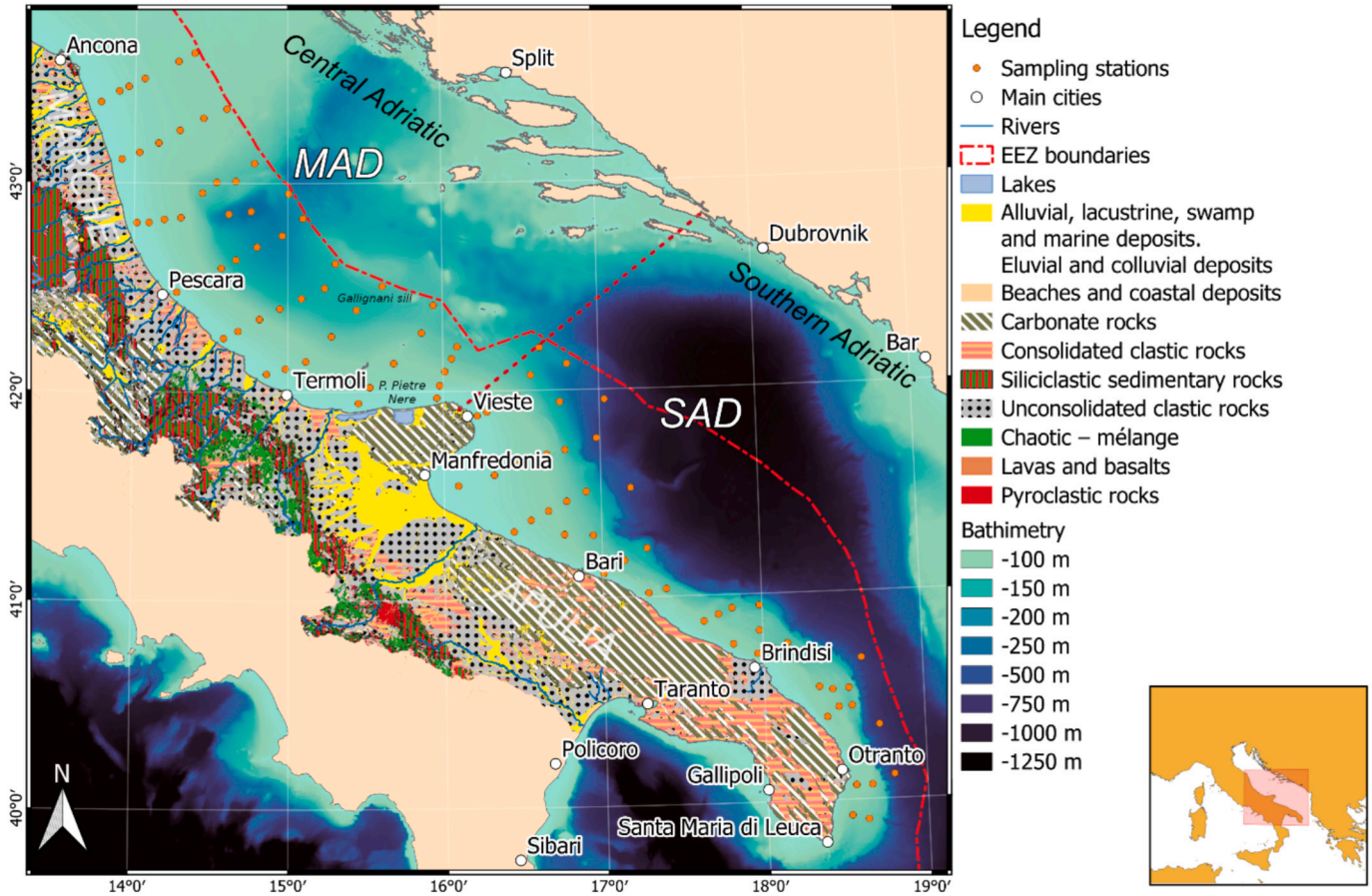


Fig. 2. Sediment sampling stations of PERTRE cruise. Geology of Italy from Bucci et al. (2022) modified; bathymetry data from https://www.gebco.net/.

AXIOS 4000 spectrometer at the XRF laboratory of the BiGeA Department, University of Bologna.

The amount of volatile substances (moisture and reticular water, organic matter, and carbonates) present in the sample was determined thorough LOI (Loss on Ignition) analysis. LOI was assessed gravimetrically by weighing pulverized sediment samples before and after heating them at 950 °C for two hours (Hoogsteena et al., 2015).

TC and TOC were determined by combustion of bulk and acidified samples following the method of Moritz et al. (2024) using a Shimadzu TOC-VCPH analyzer equipped with the SSM-5000 A specific module for solid samples at the Marche Polytechnic University, Faculty of Agriculture (Ancona, Italy). Total Inorganic Carbon (TIC) was calculated by difference.

3.3. Statistical processing

To identify sedimentary facies, biogeochemical and sedimentological parameters were statistically processed using a multivariate Q-mode factor analysis (Davis, 1986). This processing aims to recognize the relationships between the variables and by simplify a large array measured on many samples (Davis, 1986). This method is useful for studying variables measured at different spatial points and is used in environmental geochemistry to recognize multivariate structures and indexes of processes by reducing the number of variables (Spagnoli et al., 2014).

Each factor represents a combination of variables linked for common compositional and textural properties. The discussion of the factor scores and their distribution highlight important findings, including the sediment source areas, transport and reworking processes, and biogeochemical transformations that occur both at the surface and below as early diagenesis processes.

This method enables the classification of sediments and the identification of areas with common sedimentological and biogeochemical processes so that biogeochemical and sedimentological facies can be identified (Spagnoli et al., 2014), namely as “sedimentary facies.”

The compositional variables of the sediment samples used in the factor analysis were:

1) sediment grain-size classes;
2) major and trace element concentrations, along with LOI;
3) TC and TOC.

The factor analysis was conducted in four steps, as outlined by Klovan and Imbrie (1971) and detailed in Spagnoli et al. (2014). These steps include standardizing each variable, correlating the variables using the cos Θ similarity coefficient, selecting factors with a variance sum between 90% and 95%, and performing a final rotation of the axes-factors.

The areal distribution of factor scores was plotted by using natural neighbour method interpolation without anisotropy (Surfer, ver. 10).

4. Results and discussion

The biogeochemical parameters (major and trace elements, LOI, TOC and IC) and grain-size demonstrated wide variation ranges (Table 1 in the text, Fig. S3 in Supplementary material), depending on basin location and sampling depth.

The factor analysis enabled the identification of five factors, which explain 95.60% of the total variance. Factor analysis results are presented and discussed in the following sections.

4.1. Factor 1, fine silicoclastic biogeochemical facies

Factor 1 is the most representative of the sediment, explaining 85.04% of the total variance. This factor is characterized by significant positive factor loadings of grain-size classes ranging from 7 to >10 PHI, which corresponds to fine silt and clay (Fig. 3ai). Factor 1 also exhibits significant positive factor loadings for Al_2O_3, Fe_2O_3, K_2O, TiO_2 and SiO_2, as regards the major elements, and Ga, Zn, Rb, Pb, Th, Nb, V, Y, Ba, Co, Ce, Cu, As and La for the trace elements. This association indicates a silicoclastic fine-grained sediment, primarily composed of clay minerals.

Factor 1 shows negative loadings for CaO, Sr, Sc, and TIC, which are variables generally associated with carbonates, as well as grain-size classes between < −1 and 6 PHI, corresponding to gravel, sand, and coarse and medium silt.

The highest Factor 1 scores display a spatial distribution (Fig. 3bii) that delineates a belt parallel to the Italian coastline in the Central Adriatic, located north of the MAD, This belt broadens between the MAD and the Gargano promontory up to the midline and extends southward along the Puglia coast, with an interruption in front of Monopoli.

Table 1
Statistical summary of grain-size, geochemistry and biochemistry data of the sediment samples collected during the PERTRE cruise (analytical data in Supplementary material).

	Mean	Median	Standard deviation	Minimum	Maximum
Grain-size (phi) (wt%)					
Phi <−1	0.42	0.05	0.88	0	4.57
Phi 0–1	0.33	0.06	0.90	0	5.76
Phi 1–2	0.92	0.17	2.70	0	16.86
Phi 2–3	2.17	0.32	5	0	28.45
Phi 3–4	7.03	0.57	13.90	0.02	77.71
Phi 4–5	7.52	1.28	14.12	0.02	67.29
Phi 5–6	4.29	1.79	6.68	0.20	36
Phi 6–7	4.19	2.85	3.90	0.10	16.08
Phi 7–8	5.47	4.52	3.51	0.57	16.40
Phi 8–9	9.03	9.53	4.40	0.64	17.40
Phi 9–10	11.13	12.64	4.92	0.68	18.51
Phi 10 - >10	10.13	10.61	5.60	0.71	35.48
Phi >10	37.36	41.24	15.40	3.99	57.75
Grain-size (wt %)					
Gravel	0.42	0.05	0.88	0	4.57
sand	17.98	2.85	25.44	0.07	83.59
silt	22.99	19.91	11.41	4.08	55.07
clay	58.62	68.16	24.02	5.86	87.48
Geochemistry					
SiO_2 (wt%)	39.24	40.21	4.63	16.41	50.93
TiO_2	0.48	0.49	0.072	0.16	0.59
Al_2O_3	11.31	11.82	1.83	4.85	13.84
Fe_2O_3	4.95	5.24	0.79	2.49	6.22
MnO	0.14	0.11	0.08	0.07	0.52
MgO	3.37	3.24	0.52	2.45	4.98
CaO	12.60	11.30	3.67	8.15	29.80
Na_2O	1.40	1.36	0.44	0.59	2.87
K_2O	1.87	1.93	0.23	1.05	2.34
P_2O_5	0.13	0.14	0.01	0.07	0.16
LOI	24.51	24.33	3.51	17.09	39.07
As (mg/kg)	17.8	17.6	5.8	7	37
Ba	238.4	248.8	43.8	29	329
Ce	56.3	55.5	10.2	30	82
Co	11.5	12.1	2.8	4	19
Cr	122.8	118.9	27.9	63	274
Cu	13.8	14.7	4.9	2	29
Ga	13.8	14.9	2.9	6	17
La	26.2	25.0	6.5	14	41
Nb	14.1	14.3	2.3	8	19
Ni	80.4	70.5	38.8	20	246
Pb	24.6	26.3	4.7	13	33
Rb	96.6	105.4	20.1	34	120
Sc	35.0	33.6	8.8	24	87
Sr	437.6	358.9	196.7	265	1317
Th	18.3	19.6	4.7	3	25
V	91.7	95.2	14.1	47	114
Y	22.9	23.7	2.6	13	27
Zn	77.5	86.7	21.8	18	104
Zr	107.5	104.0	28.2	23	222
Biochemistry (wt %)					
IC	4.29	3.67	0.87	3.31	8.69
TOC	0.67	0	0.38	0.00	1.92

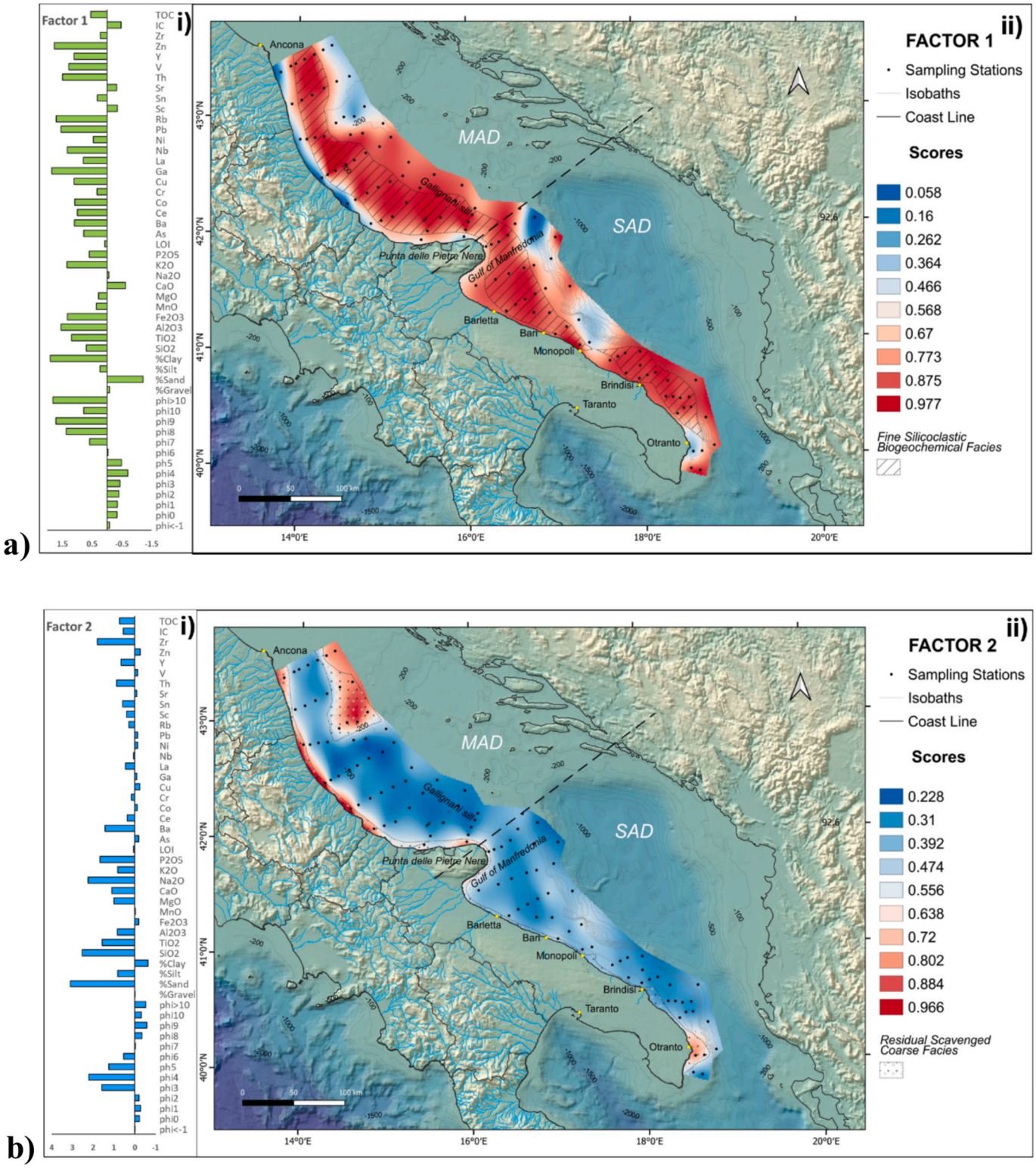
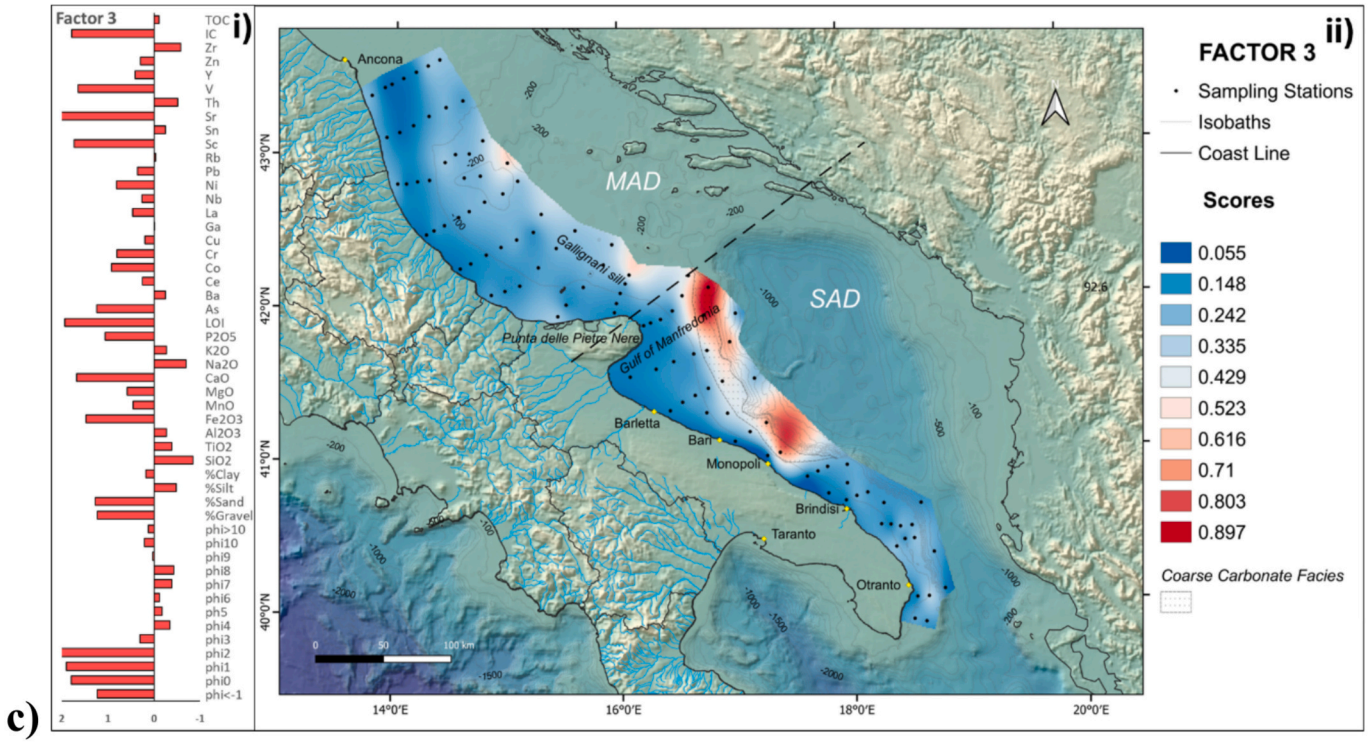


Fig. 3. Loading values (i) and score areal distribution (ii) of Factor 1 (a), Factor 2 (b), Factor 3 (c), Factor 4 (d), and Factor 5 (e).

Additionally, it exhibits low values close to the coast.

Considering the association of the variables that indicate the prevalence of fine silicoclastic minerals and the areal distribution of the Factor 1, which is similar to clay fractions (for a more comprehensive presentation and discussion of the grain-size data, refer to the paragraph titled "SA. Grain-size distribution results and discussion" and Fig. S1 in the Supplementary materials), it can be inferred that the Factor 1 identifies a specific association that can be named "Fine Silicoclastic Biogeochemical Facies". The distribution of this facies is controlled by specific sedimentological processes, morphological setup, and sediment sources.

The high-value Factor 1 belt is attributed to the suspended load that



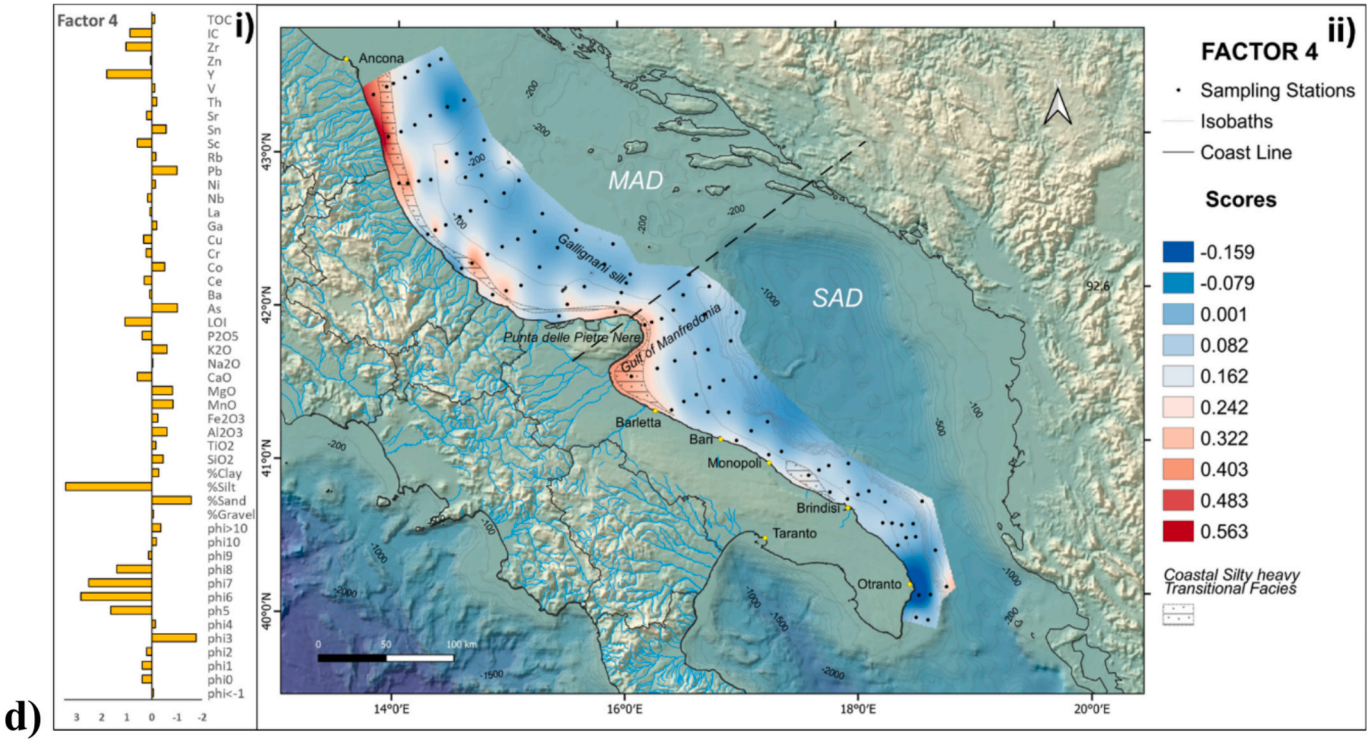


Fig. 3. (*continued*).

is transported and deposited southward by the WAC and NAdDW Adriatic currents. This can be deduced from the areal correspondence of the high values in the Fine Silicoclastic Biogeochemical Facies and the paths of the WAC and NadDW. Additionally, the statistical association of the Factor 1 exhibits a very similar factor loading composition and distribution as the Padanic Facies identified by Spagnoli et al. (2014). Therefore, the Fine Silicoclastic Biogeochemical Facies can also be regarded as being composed of sediments primarily introduced into the Adriatic Sea by the Po River. These sediments are subsequently distributed southward by the WAC and NadDW, with an increasing contribution from Apennine rivers, as already reported by Frascari et al. (2000), Ravaioli et al. (2003), Frascari et al. (2006), and Spagnoli et al. (2014).

In the Central Adriatic, from Ancona to the Gargano Promontory, the

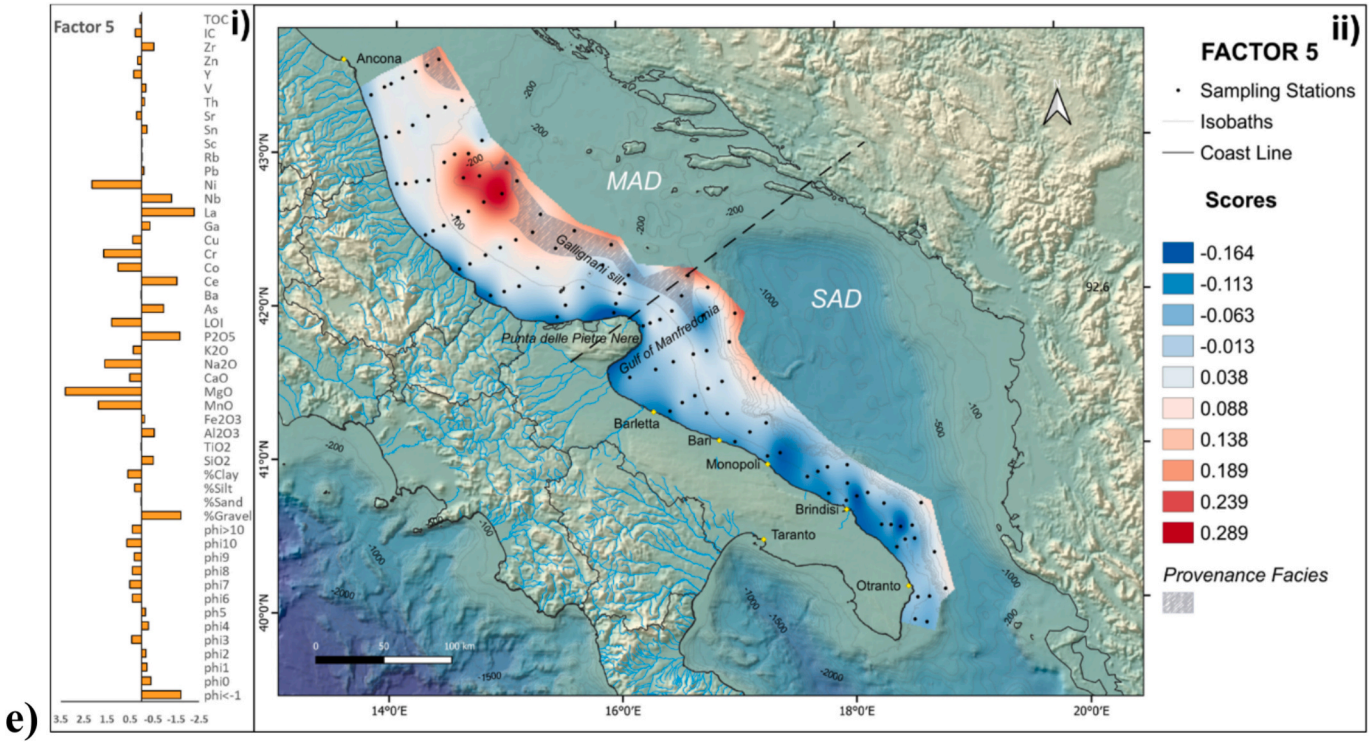


Fig. 3. (*continued*).

Fine Silicoclastic Biogeochemical Facies is separated from the coast by a continuous narrow strip characterized by very low scores. The low values of the Fine Silicoclastic Biogeochemical Facies near the coast are attributed to the shallower depths, and then to the increasing wave motion affecting the seabed. Fine silt and clay silicate minerals deposited near the coast in spring and summer, are resuspended by the fall and winter storms and subsequently moved offshore by local coastal currents as well as microtidal currents (Marcaccio et al., 2003). These suspended sediments are then captured and transported southward by the WAC and NAdDW Adriatic currents as also noted by Frascari et al. (2006).

South of the Gargano Promontory, the narrow coastal belt is nearly absent, at least up to the depths sampled, before reappearing in front of the town of Otranto. The reduction and disappearance of this coastal area south of the Gargano Promontory can be attributed to the blocking effect of the Gargano Mountains, which inhibit the passage of northern winds. This blockage creates a low-energy zone where fine materials from the Fine Silicoclastic Biogeochemical Facies can settle.

In the offshore area north of the MAD, at depth shallower than 120 m, as well as in the MAD, the Fine Silicoclastic Biogeochemical Facies decreases rapidly (Fig. 3bii). This phenomenon occurs due to the specific hydrodynamic competence of the WAC, which captures and transports fine particles southward, thereby preventing their propagation and settlement to the east. This process is highlighted by the frequency of the grain-size PHI classes of the bottom sediments, which indicates a trend from west (close to the coast) to east (offshore). As shown by the grain-size data from the northernmost transect (Fig. 4), and also in the transects of Figs. S2a and S2b of Supplementary material, the sediments exhibit a progressive increase in finer grain-size classes from station S26 to station S21. These stations display a single mode within the grain-size classes, transitioning from 4 PHI (very fine sand) to the 9 PHI class (clay). It should be noted that the finest fraction >10 does not represent a mode; rather, represents a cumulative value of all the >10 PHI classes. In station S20, a second coarser mode appears, which occurs in the sand fractions (3–4 PHI). This bimodality increases progressively eastward, reaching the maximum in the center of the basin where the finer mode disappears (station S25). The appearance of this bimodality suggests

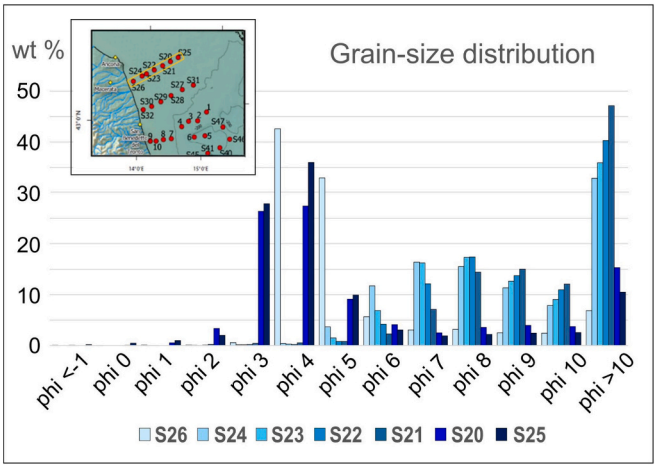


Fig. 4. Grain-size distribution (PHI scale, Krumbein, 1934) of surface sediment samples along the northernmost transect (a).

that the current fine sediment inputs are very scarce in the eastern areas, and this is attributed to the inshore fine particle confinement operated by the WAC. In this central area, bioturbation and bottom currents are able to mix the scarce recent fine sediments with the underlying relict sediments. The fine sediments only reach this area sporadically during major storms or, conversely, in the event of low hydrodynamics coupled with flood river inputs so that the Apennine and Po river plumes can reach the central areas of the basin.

In the Central Adriatic, south of the MAD slope, the Fine Silicoclastic Biogeochemical Facies extends towards the center of the basin, where a progressive deepening of the seabed is present. This pattern is also attributed to the WAC and NAdDW currents, which flow into the deeper area where they slow down, facilitating the deposition of finer sediments originating from the north. Weaker Fine Silicoclastic Biogeochemical Facies values are observed in the structural morphological highs near

the midline from the MAD to the SAD (the Gallignani Sill). These lower values are attributed to the fact that these two currents arrive in these areas very weakly and, at this stage, are free of most of the suspended solid load.

In the Southern Adriatic, the Fine Silicoclastic Biogeochemical Facies belt disappears rapidly in the outer shelf (Fig. 3bii). It suddenly close at a depth of about 200 m on the north and at shallow depths against the coast in front of Monopoli, on the south (Fig. 3bii). On the southernmost Apulia shelf, a continuous area with high Fine Silicoclastic Biogeochemical Facies values reappears; it extends from close to the coastline to the shelf and to the slope.

The offshore Fine Silicoclastic Biogeochemical Facies scarcity are attributed to the action of the Southern Adriatic Gyre. This current, with very low suspended particle content (De Lazzari et al., 1999), pushes the WAC westward (Kalimeriskosterin and Kassis, 2020), preventing the deposition of fine suspended particulate on the outer shelf.

This latter facies is composed of fine sediments that are either removed by wave motion at the shallower depths of the two coastal facies or are directly sourced from the fluvial plumes of the Po and Apennine rivers and, to a lesser extent, from the Eastern Alps. All these sediments are transported southward by the WAC and the NAdDW.

In the Central Adriatic offshore, north of the MAD, the action of the WAC prevents the eastward diffusion of fine sediments. This occurs through the selective capture and southward transportation of suspended solids, leading to the formation of another facies that results from older processes: the Relict Residual Scavenged Carbonate Sandy Sub-Facies.

4.2. Factor 2, residual scavenged coarse facies

Factor 2 accounts for 5.80% of the total variance. This factor is characterized by positive loadings as regards the sandy fractions and the grain size classes ranging from 3 (very fine sand) to 6 PHI (medium silt) (Fig. 3bi). Among the elements, positive loadings are notable for SiO_2, followed by Na_2O, Zr, P_2O_5, TiO_2, and Ba. Additionally, significant positive loadings are observed for Al_2O_3, MgO, CaO, K_2O, Th, and Y.

The strong affinity of this factor for very fine sand and medium silt grain-sizes indicates that these sediments result from selective wave energies that remove particles that are finer than 6 PHI. Furthermore, the geochemical association of Zr, Ba, P_2O_5, and partially CaO, in this factor suggests a co-presence of fine heavy minerals (zircon, garnet, barite, and apatite) rich in Zr, Ba, and P (Beltagy et al., 1983; Poulsen et al., 2007), and coarser but lighter minerals (quartz and plagioclase) deposited in high-energy conditions. These minerals have varying specific weights and grain-sizes; however, they are expected to display similar hydrodynamic behavior, allowing for their selective sorting within a coastal high-energy environment, as has been frequently observed (Garcia et al., 2004; Lim et al., 2013). This Factor is then indicative of the reworking and removal of fine sediments, which can be referred to as Residual Scavenged Coarse Facies.

This facies can be divided into two sub-facies on the basis of the two different areal distributions: the Coastal Residual Scavenged Coarse Facies, close to the coast, and the Relict Residual Scavenged Carbonate Sandy Sub-Facies, in the lag and scavenged deposits of the central basin north of the MAD (Fig. 3bii).

North of the Gargano Promontory, the distribution of the Coastal Residual Scavenged Coarse Facies increases in depth from approximately 15 m of the Central Adriatic, up to 20 m on the north of the Gargano Promontory. This change is attributed to the heightened wave action resulting from the longer southward fetch of the northern winds. In contrast, to the south of the Gargano, the Coastal Residual Scavenged Coarse Facies practically disappears. This is attributed to the Gargano mountains obstructing the northern winds and to the presence of coastal biochemical constructions (Colantoni, 1990).

Other weak high values of this facies are found in a belt on the external shelf surrounding the western edge of the SAD (Fig. 3bii). This occurrence is attributed to the confinement of the WAC and the sweeping action of the Southern Adriatic Gyre.

A focus on the spatial distribution of MgO, CaO, Zr, and Ba (Fig. 5) provides some additional details to this facies. This facies shows a discrete association with MgO and CaO, although these elements show different distributions (Fig. 5a and b). The highest MgO concentrations are localized to the north of the MAD, at depths shallower than 120 m, in the MAD, along the Gallignani Sill, and along the northern upper slope of the SAD. Unlike MgO, CaO distribution also shows high concentrations along the coastal area of the Central Adriatic. The association of MgO and CaO in this facies in the Central Adriatic, north of the MAD, is attributed to pre-Holocene dolomitic contributions coming from the Eastern Alps and not present in the poor post-Holocene fine sedimentation in this area (Pigorini, 1968; Ferretti et al., 1986; Colantoni, 1990; Trincardi et al., 1996; Tomadin, 2000; Lucchini et al., 2003; Ravaioli et al., 2003; Maselli et al., 2011). Furthermore, the low concentrations of MgO near the coast are the result of the near total absence of dolomitic contributions from the Eastern Alps, as reported by Goudeau et al. (2013) and Harris et al. (2008).

Zr is concentrated near the coast of the entire Western Adriatic and in the central area north of the MAD, with higher values in the coastal area around the Gargano Promontory. As regards the Ba, without considering the typical area of the Fine Silicoclastic Biogeochemical Facies, whose high Ba concentrations are attributed to the clay mineral component, it can be noted that the Ba is concentrated along the coast, extending only from the Gargano Promontory to the south. Zr is a principal component of the zircon, a common detrital heavy mineral; this accounts for its presence in the coarse selected sediments of the Coastal Residual Scavenged Coarse Facies. Furthermore, Zr-rich volcanic rocks outcrop at the *Punta delle Pietre Nere,* located on the northern border of the Gargano Promontory, where gabbros and syenites of lamprophyric affinity are outcropping (Bianchini et al., 2008; Mazzeo et al., 2018), and on the Monte Vulture area (De Fino et al., 1986; Melluso et al., 1996; De Astis et al., 2006), which provides sediments to the Ofanto River and then to the area south of the Gargano Promontory (Spagnoli et al., 2008). The Punta delle Pietre Nere accounts for the elevated Zr concentrations in the narrow belt close to the Gargano Promontory (Fig. 5c), while, the inputs from the Ofanto River may be responsible for the high concentrations observed along the Puglia coastline. These sources are also significantly enriched also in Ba (see previous references), which explains the marked increase in Ba levels south of the Gargano (Fig. 5d).

The above discussions demonstrate how a detailed analysis of the spatial distribution can aid in the interpretation of the Factor 2 as a "Residual Scavenged Coarse Facies" formed in a high-energy environment and subsequently enriched in heavy particles for the removal of the finest sediments (the so-called lag deposits).

4.3. Factor 3, bimodal carbonate facies

Factor 3 accounts for 2.60% of the total variance. This factor exhibits positive loadings for sandy-gravelly sediments, as well as grain-size classes ranging from < -1 to 2 PHI. It includes positive association also with elements such as Sr, CaO, V, and Sc, and with LOI and IC. Additionally, lower positive values are observed for Fe_2O_3, As, and P_2O_5 (Fig. 3ci), and minimally for clay and PHI >10.

Negative factor loadings pertain to SiO_2, Na_2O, TiO_2, Zr, Th, Al_2O_3, and K_2O (Fig. 3ci).

The significant positive loadings of CaO, along with elevated levels of Sr, LOI, and IC, contents denote a substantial presence of carbonate minerals. Consequently, Factor 3 can be regarded as representative of carbonate minerals found in coarser sediments and to lesser extent in the clay fraction. For these reasons, this factor is called "Bimodal Carbonate Facies".

The Bimodal Carbonate Facies generally exhibits low scores, with spatial distribution increasing in offshore areas (Fig. 3cii): i) on the sill of the MAD; ii) on the Gallignani Sill; and iii) on the outer shelf of the

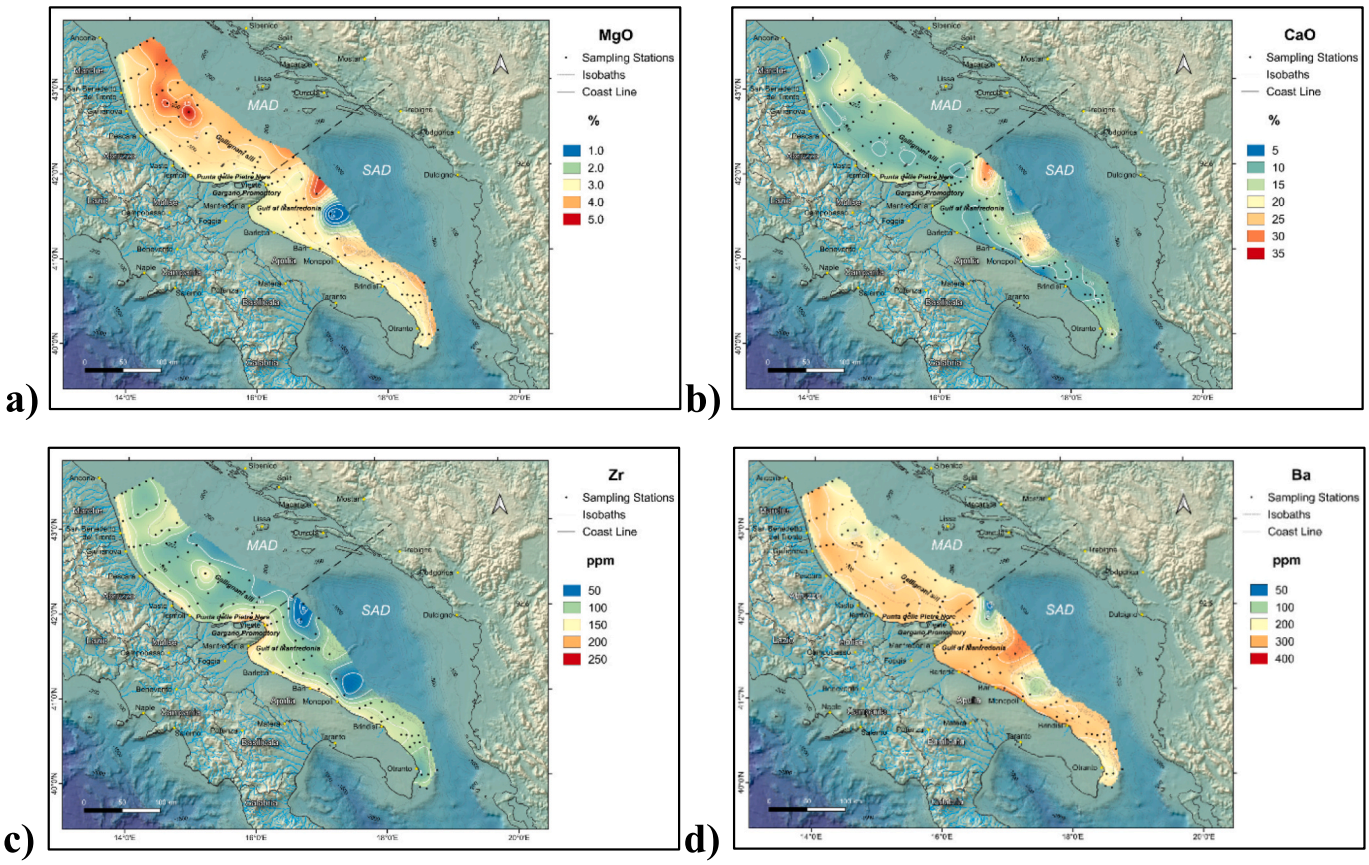


Fig. 5. Areal distribution of MgO (a), CaO (b), Zr (c), and Ba (d).

Southern Western Adriatic where the scores reach the highest values.

The distribution of the Bimodal Carbonate Facies indicates that it originates from limited fine sediment deposition and occurs in areas where older coarse substrates are exposed and coarser bioclasts and biosomes accumulate in relation to the finer particles (Colantoni and Gallignani, 1978).

As already specified for the low Fine Silicoclastic Biogeochemical Facies values, this phenomenon is attributed to the limited fine terrigenous inputs that are caught and transported southward by the WAC. On the outer shelf bordering the SAD, the low accumulation rate of fine sediments is intensified by the action of the Southern Adriatic Gyre (SAG), which pushes the WAC westward and sweeps the bottom sea removing the finer sediments.

Also in this case, the discussion on individual elements, specifically CaO and Sr (Fig. 6), adds further insights into this facies. The biogenic origin of the carbonate content in this facies is supported by the high ratios of Sr and CaO, which are characteristic of biogenic aragonitic origin rather than abiotic carbonates. The Sr and CaO diagram (Fig. 6a), not only highlights the positive correlations but also reveals the presence of two distinct groups, separated by the 4.7 line of the Sr/Ca ($*10^{-3}$)

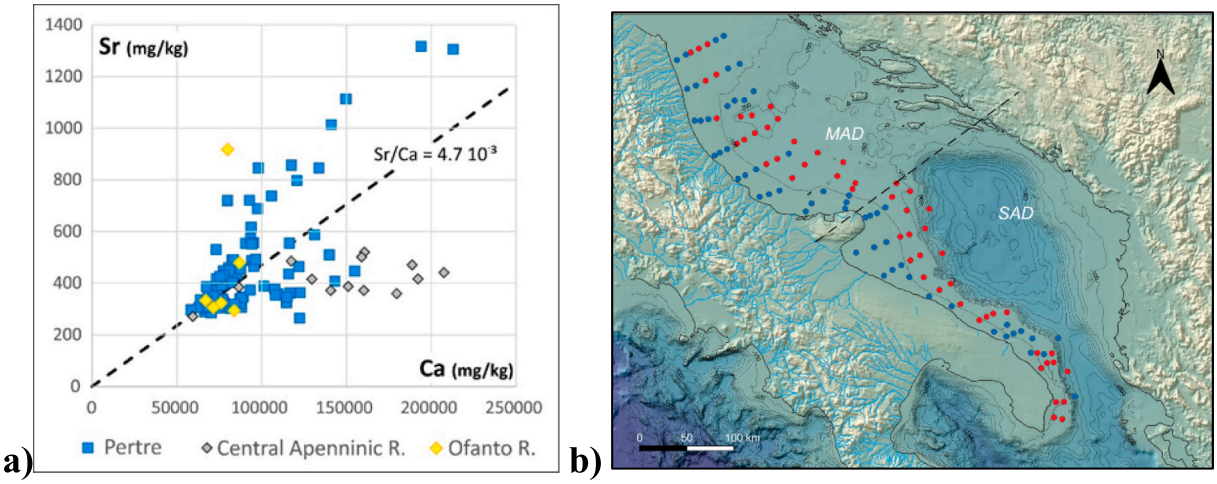


Fig. 6. a) Sr vs. Ca diagram, with the indication of the 4.7 Sr/Ca ratio ($*10^{-3}$) (dotted line) (blue squares: PERTRE samples; grey diamonds: Apennine rivers; yellow dots: Ofanto River); b) dot map of the Sr/Ca ratio (blue dots <4.7, red dots >4.7). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ratio.

These two clusters and their distinct areal distribution support the different detritic and biological origins of the carbonate minerals. Lower ratios that indicate the detritic origin coming from continental inputs (Dinelli and Lucchini, 1999), are prevalent near the coast (Fig. 6b), where river inputs are dominant. Higher ratios, indicating an increasing biogenic aragonitic carbonate component, are diffused in the deeper and offshore areas of the Adriatic (Fig. 6b), where pelagic inputs are more important. This observation is also supported also by other studies that have highlighted similar results in other seas, showing Sr/Ca $\geq$ 5.2 in deep seas rich in foraminifera and coccolithophores (Turekian, 1964; Kim et al., 1999), or values comparable to those presented for surface sediments by Rutten et al. (2000) in the eastern Mediterranean.

4.4. Factor 4, coastal silty heavy transitional facies

Factor 4 accounts for 1.19% of the total variance. This factor is characterized by high positive loadings of silty sediments, grain-size classes from 5 (coarse silt) to 8 (very fine silt) PHI, and yttrium among the geochemical elements (Fig. 3di). These variables exhibit strong positive weights, which prevail over all the others such as the weaker positive weights of LOI, Zr, Sc, IC, CaO, and P_2O_5.

Factor 4 shows significant negative scores for the sandy fraction, grain-size 3 PHI class, and moderate negative scores for geochemical elements such as As, Pb, MnO, MgO, Sn, Al_2O_3, and Co (Fig. 3di).

Factor 4 is strongly correlated (Fig. 3di) and shows similar areal distribution with the silty fractions (SA. Grain-size distribution results and discussion and Fig. S1, in Supplementary material). Its spatial distribution (Fig. 3dii) displays high values close to the Adriatic coast. However, this facies is located slightly offshore with respect to the Coastal Residual Scavenged Coarse Facies. The maximum values are present in front of the Marche Region, between the Chienti and Tronto rivers. High values are also present in a strip separated from the coast, between Vasto and Termoli, along the coast of the Gargano Promontory and of the Gulf of Manfredonia. Other slightly higher concentrations can be found along the Central Adriatic sills and in the northern and outer shelf of the Southern Adriatic.

The granulometric and geochemical compositions of Factor 4 indicates a silty fraction that is characterized by heavy minerals such as garnet. The presence of garnet is supported by the strong correlation of this factor with the Y. The occurrence of garnet, as well as Y, in the coastal sediments of the central and southern Adriatic is reported by Pigorini (1968), who recognized the importance of this mineral along the Marche coast, south of Ancona, and in southern coastal areas (Vasto and Termoli). Brondi et al. (1979) highlighted the importance of this mineral in beach sands. In addition, the Punta delle Pietre Nere and the Ofanto River serve as important sources (Mazzeo et al., 2018; Spagnoli et al., 2008), as Spagnoli and Andresini (2018) identified relatively high Y content in the sediments of the Lesina Lagoon, which are influenced by the outcrops of Punta delle Pietre Nere.

The formation of this facies is then attributed to the wave action of major storms occurring at greater depths, where the process of selective removal of fine particles is less pronounced. This action removes silt and heavy minerals from the shallower coastal area, where the Coastal Residual Scavenged Coarse Facies prevails, and allows the selective deposition of silty sediments and heavy minerals that exhibit the same hydrodynamic behavior. These particles are then deposited in a deeper belt between the Coastal Residual Scavenged Coarse Facies and the Fine Silicoclastic Biogeochemical Facies. In this belt, the wave action is weak enough to leave the silty heavy mineral component but not enough for finer materials, which are deposited at greater depths and distances from the coast. Following these interpretations, this factor can be called "Coastal Silty Heavy Transitional Facies".

4.5. Factor 5, provenance facies

Factor 5 accounts for 0.97% of the total variance. This factor is characterized by high positive loadings of MgO, MnO, Na_2O, CaO, LOI, Ni, Cr, and Co (Fig. 3ei). To a lesser extent, this factor is characterized by positive scores of clay and silty fractions and relatively coarse-grained classes (6, 7, 8, 9, 10, $>$ 10 PHI, i.e., from medium silt to clay). This factor shows negative scores for SiO_2, Al_2O_3, P_2O_5, As, Ce, La, Nb, and particularly for gravel.

The Factor 5 areal distribution reveals high values in four different areas of the Adriatic Sea (Fig. 3eii): i) in the northeasternmost side of the study area, that is in the Central Adriatic, north of the MAD; ii) in the area of the MAD, where maximum values are recorded; iii) in the area of the Gallignani Sill highs; and iv) in the upper slope of the SAD.

The very low loadings of all grain-size classes in the Factor 5, along with the absence of matches between Factor 5 and any grain-size class areal distribution (Fig. 3ei), suggest that the sediments associated with this factor have different origins.

The positive association of MgO (Fig. 5a), CaO (Fig. 5b), MnO (Fig. 7a), and LOI in the offshore region of the Central Adriatic Sea, north of the MAD, is attributed to pre-Holocene contributions of dolomite coming from the Eastern Alps. This mineral was particularly abundant in the area during the last glacial period (Lucchini et al., 2003), as was for the Relict Residual Scavenged Carbonate Sandy Sub-Facies. The notable presence of coarse-grain-size sediments in this area (SA. Grain-size distribution results and discussion and Fig. S1, in Supplementary material) confirms the selective removal of the finer sediments during the last marine transgression, along with the subsequent low inputs of fine sediment inputs as discussed for the Relict Residual Scavenged Carbonate Sandy Sub-Facies.

The positive association of MgO (Fig. 5a), CaO (Fig. 5b), MnO (Fig. 7a), LOI, and fine sediments (Fig. S1, Supplementary material) in the MAD is attributed to the current deposition of very fine sediments from diverse sources and processes; this gives rise to three main groups: carbonate-rich, MnO-rich, and heavy metal-rich (Cr, Ni and Co) fine sediments.

Fine carbonate sediments are interpreted as resulting from the deposition of detritic carbonates, originating from the eastern Dolomitic Alps and Apennines, as previously reported by Brondi et al. (1979), Dinelli and Lucchini (1999), Brambati et al. (1973), Pigorini (1968), and Ravaioli et al. (2003), and from biogenic intrabasinal carbonates such as coccolithophorids, as reported by Spagnoli et al. (2014).

MnO-rich fine sediments are interpreted as resulting from: i) the deposition of fine Mn oxides and oxyhydroxides in the low-energy environment of the MAD. These Mn oxides and oxyhydroxides precipitate during the summer at the sediment-water interface, in areas located off the coast of the Emilia-Romagna and Marche regions. Then they are resuspended by fall and winter storms (Spagnoli and Bergamini, 1997), to be transported southward by the WAC and NAdDW (Spagnoli et al., 2014); ii) local direct authigenic precipitation of Mn oxides and oxyhydroxides near the sediment-water interface through early diagenesis processes (Spagnoli et al., 2014). In this context, Dolenec (2003) examined the origin of Mn-encrusted fossils in the MAD area, while Lucchini et al. (2003) and Ilijanić et al. (2014) observed marked surface enrichment across several cores, which has been associated with early diagenetic remobilization and precipitation.

High concentrations of Cr, Ni and Co in the MAD and on the Gallignani Sill (Figs. 7b, c, and d) are attributed to the deposition of fine detrital sediments originating from the volcanic and metamorphic rocks of the Balkan hinterlands (Wedepohl, 1978; Dolenec et al., 1998; Halamic et al., 2012; Amorosi et al., 2022), the submarine weathering of the basaltic rocks of the Jabuka, Vis, Brusnik and Svetae islands (Dolenec et al., 1998; De Min et al., 2009; Lozić et al., 2012), and the serpentinites and peridotites found in the Western Alps and Northern Apennines. (Amorosi et al., 2002; Lucchini et al., 2003; Dinelli et al., 2007; Weltje and Brommer, 2011; Amorosi, 2012; Goudeau et al.,

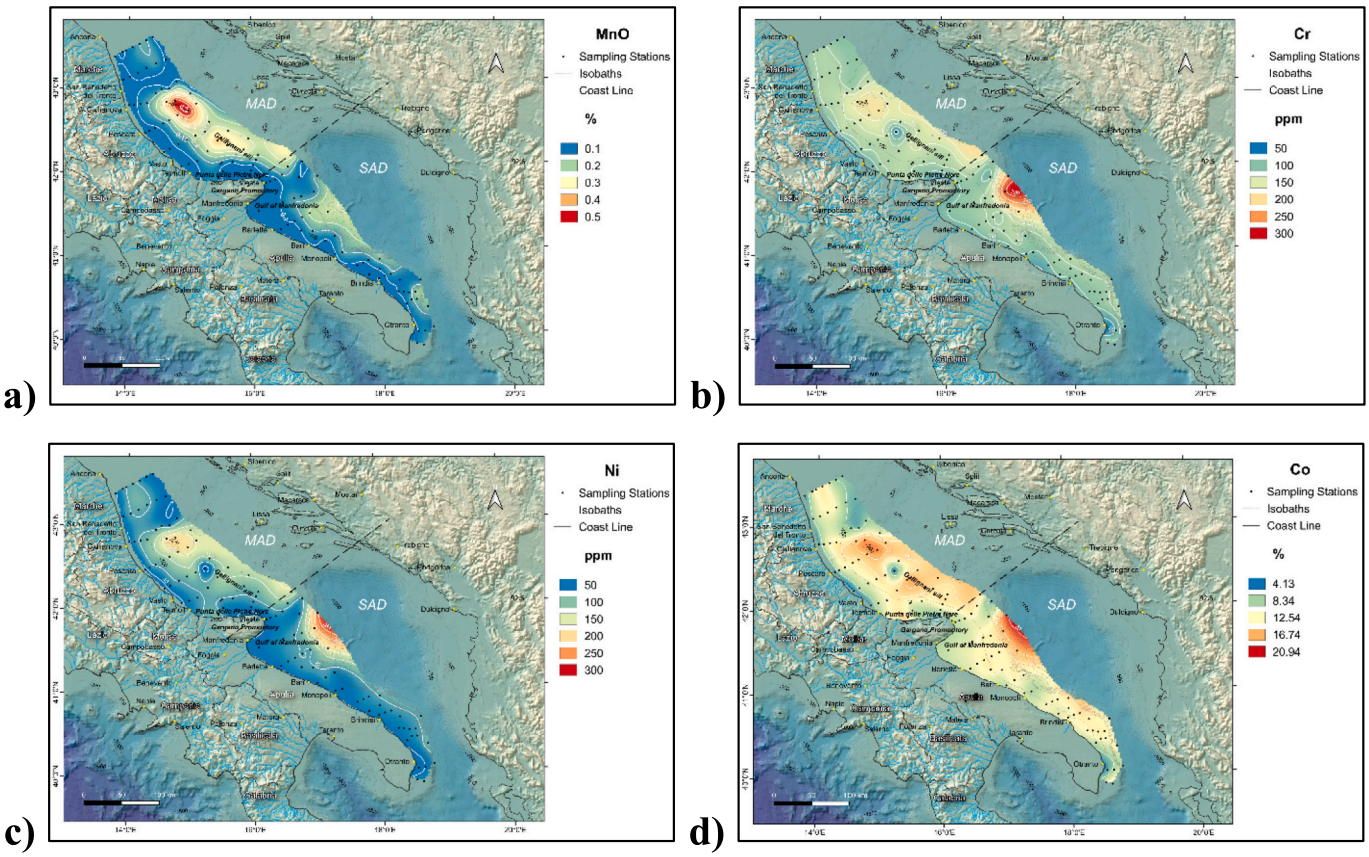


Fig. 7. Areal distribution of MnO (a), Cr (b), Ni (c) and Co (d).

2013). High concentrations of Cr, Ni and Co prevail also in a local area along the upper slope of the SAD in the southern Adriatic (Fig. 7b, c, and d), in sediments characterized by crusts, variable grain-size, and over consolidated clays (Spagnoli et al., 2016). In particular, the sample collected in station S92, where the maxima of Cr, Ni, and Co are found, is characterized by partially cemented silty-sandy sediments, and it is located on the upper side of the Gondola Slide (Dalla Valle et al., 2015). Therefore, this area is likely affected by the outcrop of pre-Holocene sediments, which have been uncovered by gravitational processes along the upper edge of the slope.

Based on the observations reported above, Factor 5 is related to sediments strongly controlled by different source areas and is therefore identified as a "Provenance Facies".

5. Biogeochemical and sedimentological integrated map of the Adriatic Sea

The areal distributions of the biogeochemical and sedimentological facies identified by the statistical analysis, combined with the morphological setup of the Adriatic Sea, can be synthetized in an integrated map of the Italian side of the Adriatic Sea from Ancona to Otranto (Fig. 8).

From the coast to the offshore, along a belt roughly parallel to the Italian coast, it is possible to highlight the juxtaposition of five sedimentary facies (Fig. 8).

The Coastal Residual Scavenged Coarse Facies (Facies 2a and 2b in Fig. 8), resulting from the reworking and removal of finer sediments by the wave motion at the shallow depths close to the Italian coast. This facies is composed of coarse grains derived from local rivers; It develops continuously from Ancona to the Gulf of Manfredonia, while its development is irregular further south (Fig. 8).

The Coastal Residual Scavenged Coarse Facies can be differentiated in two sub-facies: The northern Coastal Residual Scavenged silicoalkaliclastic Sub-Facies (Facies 2a in Fig. 8) and the southern Coastal Residual Scavenged silicovolcanic Sub-Facies (Facies 2b in Fig. 8). The northern Coastal Residual Scavenged silicoalkaliclastic Sub-Facies is characterized by sandy and partially silty heavier minerals with elevated CaO contents due to the inputs of alkali-rich aluminosilicate minerals from local Central Apennine rivers. The southern Coastal Residual Scavenged silicovolcanic Sub-Facies) is rich in Zr and Ba due to the inputs of volcanic rocks from Punta delle Pietre Nere and Monte Vulture-Ofanto River.

Moving to the east, the Coastal Residual Scavenged Coarse Sub-Facies is superseded by the Coastal Silty Heavy Transitional Facies resulting from the wave action generated by major storms.

In the Central Adriatic, to the north of the Gargano Promontory, the two Coastal Residual Scavenged Coarse Facies and Coastal Silty Heavy Transitional Facies increase in depth from approximately 15 m to 20 m. This increase is attributed to the southward enhanced fetch and strength of the northern winds. Conversely, south of the Gargano Promontory, these two coastal facies are nearly absent, as the Gargano Promontory hinders the action of the northern winds.

Further eastward, the Coastal Silty Heavy Transitional Facies gradually transitions into the Fine silicoclastic Biogeochemical Facies (Facies 4 in Fig. 8).

The Fine Silicoclastic Biogeochemical Facies extends along a belt from the Monte Conero to south of Bari, in front of Monopoli, to then reappear further south. The sediments belonging to this facies originated mostly from of the Po River and the Apennine rivers to be transported and settled by the general Adriatic anticyclonic circulation.

The Fine Silicoclastic Biogeochemical Facies extends eastward into the Central Adriatic Sea in various ways due to different dispersal processes on the sea bottom, which are influenced by changes in morphology and depth (see paragraph 4.1).

In the Central Adriatic offshore, north of the MAD, at depths

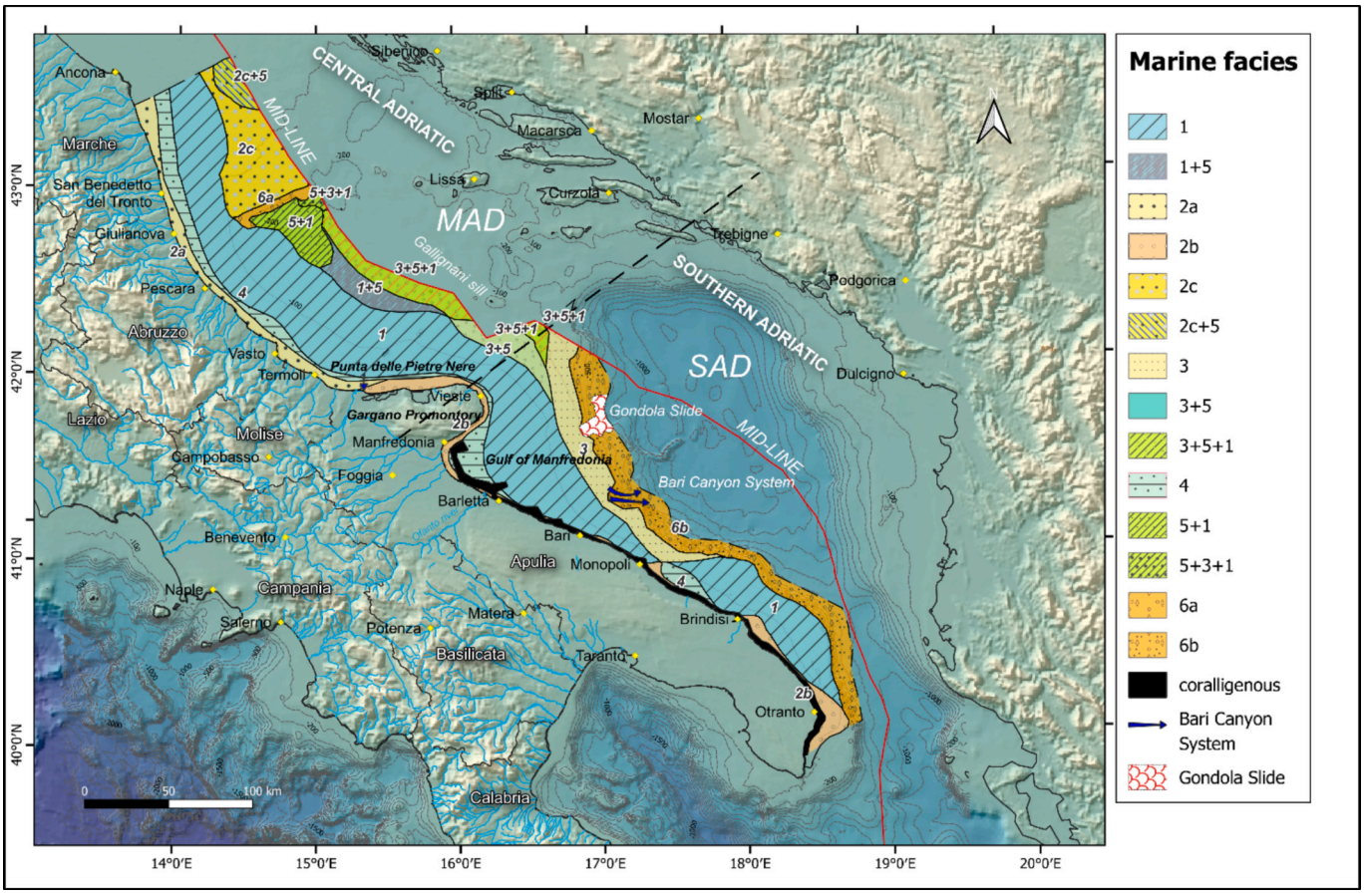


Fig. 8. Distribution of surface sediment biogeochemical/sedimentological facies of the Central and Southern Adriatic Sea. 1: Fine Silicoclastic Biogeochemical Facies; 2: Residual Scavenged Coarse Facies, divided into: 2a: Coastal Residual Scavenged silicoalkaliclastic Sub-Facies, 2b: Coastal Residual Scavenged silicovolcanic Sub-Facies, 2c: Relict Residual Scavenged Carbonate Sandy Sub-Facies; 3: Bimodal Carbonate Facies; 4: Coastal Silty heavy Transitional Facies; 5: Provenance Facies; 5 + 1: Provenance Facies partially mixed with Fine Silicoclastic Biogeochemical Facies (Provenance and Fine Silicoclastic Facies); 1 + 5: Fine Silicoclastic Biogeochemical Facies partially mixed with Provenance Facies; 3 + 5: Bimodal Carbonate Facies partially mixed with Provenance Facies; 5 + 3 + 1: Provenance Facies partially mixed in order with Bimodal Carbonate Facies and Fine Silicoclastic Biogeochemical Facies; 3 + 5 + 1: Bimodal Carbonate Facies partially mixed in order with Provenance Facies and Fine Silicoclastic Biogeochemical Facies; 2c + 5: Relict Residual Scavenged Carbonate Sandy Sub-Facies partially mixed with Provenance Facies; 6: Slope Facies, 6a: Northern MAD Upper Slope Facies, 6b: Western SAD Upper Slope Facies; Black Facies: shelf coralligenous or coralline calcarenite from Colantoni (1990). Gondola Slide area fromDalla Valle et al. (2015).

shallower than 120 m, recent fine silicoclastic sediments gradually disappear leading to the eastward emergence of coarser sediments of the Residual Scavenged Coarse Facies (Facies 2c in Fig. 8).

The limit delimiting these four sedimentary facies which transition is gradual and defined on the basis of the seaward changes of the grain-size classes associated with each facies (see paragraph 4.1, Fig. 4).

The Coastal Residual Scavenged Coarse Facies is characterized by grain-size classes that are finer than 6 PHI (Figs. 3bi and 4S26), while the grain-size class of the Coastal Residual Scavenged Coarse Facies are between 5 and 8 PHI with maxima in 6 and 7 PHI (Fig. 3 di and 4S24). Therefore, the limit between the Coastal Residual Scavenged Coarse Facies and the Coastal Silty Heavy Transitional Facies can be conventionally defined by the transition from the 6 PHI class (medium silt) to the 5 PHI class (coarse silt), as shown between the station S26, belonging at the Coastal Residual Scavenged Coarse Facies, and station S24, attributable to the Coastal Silty Heavy Transitional Facies, in the northernmost transect of Fig. 4.

Proceeding to the east, the Fine Siliciclastic Biogeochemical Facies is characterized by grain-size classes that are finer than 6 PHI with maxima in 8 PHI and 9 PHI. The gradual transition between these two facies can be then conventionally setup to the change from the 7 PHI to the 8 PHI classes, as shown between the station S24, attributable to the Coastal Silty Heavy Transitional Facies, and the station S23, belonging to the Fine Siliciclastic Biogeochemical Facies (Fig. 4).

The boundary between the Fine Silicoclastic Biogeochemical Facies and the Relict Residual Scavenged Carbonate Sandy Sub-Facies can be established on the basis of the eastward occurrence of the bimodal sediment grain-size towards the center of the basin, as discussed in the paragraph 4.1, that is at that is between the station S21, pertinent to the Fine Silicoclastic Biogeochemical Facies, and station S20, belonging to the Relict Residual Scavenged Carbonate Sandy Sub-Facies along the northern transect (Fig. 4), and between the stations S29 and S28 along the transect of Fig. 2a (Supplementary material) and between the stations 7 and 4 along the transect of Fig. S2b.

In the Central Adriatic, from the MAD to the Gargano Promontory, the Fine Silicoclastic Biogeochemical Facies widens towards the center of the basin (Fig. 8) due to the movement of the WAC, as well as of the NAdDW, towards the steeper and deeper seabed areas.

In the MAD, where the northern water currents reduce their hydrodynamic energy, the fine components of the Provenance Facies defined in the paragraph 4.5 (Facies 5 in Fig. 8) prevails over the Fine Silicoclastic Biogeochemical Facies.

In the morphological highs of the deep Central Adriatic, between the MAD and the SAD, the Gallignani Sill sediments are again characterized by the appearance of a grain-size bimodality due to the occurring of a coarse component, as in the Residual Scavenged Coarse Facies (Fig. S2c

in Supplementary material), indicating concomitant fine and coarser low sediment deposition due to low terrigenous inputs and intrabasinal biogenic deposition. In this area, the Fine Silicoclastic Biogeochemical Facies, the Bimodal Carbonate facies defined in the paragraph 4.3 (Facies 3 in Fig. 8) and the Provenance Facies mix in different proportions, giving rise to melted facies composed respectively of: Bimodal Carbonate Facies partially mixed, in order, with the Provenance Facies and the Fine Silicoclastic Biogeochemical Facies (Facies 3 + 5 + 1 in Fig. 8); and Provenance Facies, partially mixed, in order, with the Bimodal Carbonate Facies and the Fine Silicoclastic Biogeochemical Facies (Facies 5 + 3 + 1 in Fig. 8). In the transition area, rising from the MAD to the Central Adriatic structural highs of the Gallignani Sill, the Fine Silicoclastic Biogeochemical Facies mixes only with the Provenance Facies, giving rise to the Facies 1 + 5 (Fig. 8), indicating that the WAC and NAdDW sediment contributions occur consistently in this area.

In the Southern Adriatic, the Fine Silicoclastic Biogeochemical Facies develops along a belt that rapidly transitions eastward to the Bimodal Carbonate Facies due to the Southern Adriatic Gyre (SAG) action (see paragraphs 4.1 and 4.3), which directs the WAC westward and sweeps the external shelf sediments up to the coast south of Bari, in front of Monopoli (Fig. 8), where the Fine Silicoclastic Fine Facies meets the coastline. South of Monopoli, the Fine Silicoclastic Biogeochemical Facies reappears due to the eastward shift of the SAG.

In addition to the facies identified with the factor analysis, other facies, related to specific morphologies or generated by biochemical structures, can be delimited. As regards the morphological setting, two upper continental slope areas have been defined; they are located along the northern edge of the MAD (Facies 6a in Fig. 8), and along the western edge of the SAD (Facies 6b in Fig. 8). These areas are typically characterized by erosional and gravitational deformation structures, leading to outcrops of pre-Holocene sediments. In terms of biochemical structures, a shelf of corralligenous or coralline calcarenite, as noted earlier by Colantoni (1990), is located close to the coast of Apulia, south of the Gargano Promontory (coralligenous Facies in Fig. 8). This shelf is formed by carbonate biochemical precipitation in warmer lighter marine waters and is indicated on the map.

6. Conclusion

This paper discusses the geochemical, granulometric and biochemical composition of surface sediment of the Central and Southern Adriatic Sea.

Based on the results of a Q-mode factor analysis, five statistical factors were recognized that have been interpreted in terms of areal distribution, bottom sea morphology, continental inputs, and basin hydrodynamics.

By these findings, it was possible to propose a detailed map of the surface sediment of the Central and Southern Adriatic Sea that considers the geochemical signals associated with detrital sediment provenance, contributions from authigenic processes, biogenic inputs, and sorting processes, interpreted in light of oceanographic and morphological features.

On the whole, five biogeochemical-sedimentary facies have been identified: two coastal facies shaped by littoral hydrodynamics, leaning against the Italian shoreline and affected by local river inputs, which are: the shallower Coastal Residual Scavenged Coarse Facies, further divided into the northern Coastal Residual Scavenged silicoalkaliclastic Sub-Facies and the southern Coastal Residual Scavenged silicovolcanic Sub-Facies, and the deeper Coastal Silty Heavy transitional Facies; the Fine silicoclastic Biogeochemical Facies, characterized by clay sediments transported southward by the Western Adriatic Current and the North Adriatic Dense Water Current, extending in a belt along almost the entire Central and Southern Adriatic; the Relict Residual Scavenged Carbonate Sandy Sub-Facies, in which deposits reworked during the last sea level outcrop; the Provenance Facies, due inputs from different source areas.

To the previous knowledge, in the center of the Adriatic, a complex mixture of sediments of different provenance and sedimentological processes was identified, in particular along the Gallignani Rise, where, a dominating carbonatic composition specific signal, related to different sediment provenance, were recognized.

This research highlights the dearth of data integration concerning the Eastern Adriatic, which is largely due to the political division of the Adriatic basin among different nations. This work aspires to foster a discussion aimed at establishing a stable Pan-Adriatic research system that addresses different geological, oceanographic, biological, and other research topics.

Finally, this paper, not only presents the scientific results deriving from the analyses of the surface sediments collected in the Adriatic Sea during the PERTRE Cruise but also proposes a method to identify new interpretations of seabed sediments. This method is based on the complex interactions between terrigenous and authigenic sediment sources, basin hydrology patterns, and morphological features highlighted by a specific Q-mode factor statistical analyses.

CRediT authorship contribution statement

Elisa Droghini: Writing – original draft, Methodology, Data curation. **Giuseppe Baldelli:** Methodology, Data curation. **Rocco De Marco:** Writing – original draft, Software, Methodology, Data curation, Conceptualization. **Enrico Dinelli:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Data curation, Conceptualization. **Mario Tramontana:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **Giulio Pappafico:** Writing – review & editing, Software, Methodology, Data curation. **Federico Spagnoli:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.margeo.2026.107763.

Data availability

Data will be made available on request.

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