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Sedimentological features of asbestos cement fragments in coastal environments (Taranto, Southern Italy)

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ABSTRACT

Asbestos cement materials (ACMs) are widespread in coastal environments as result of illegal dumping activities. This study focuses on the Taranto area (Italy) in the Mar Grande basin within the northern sector of the Ionian Sea. The complex history of dumping building materials containing high amounts of ACM into the coastal zone, and the erosion, transport and deposition in Marechiaro Bay is a serious environmental hazard. An interdisciplinary research methodology defines the temporal dumping succession, and the erosional processes and phases, the diffusion of ACM, the mineralogical characteristics, and existing physical status of the ACM. A multiscale investigation was conducted. Results show that from 1992 to 2000 a significant increment of dumping operations have occurred. The current cliff has been subject to erosion and redeposition phases, developing a new beach composed of these polluted man-made sediments. The findings persuade the local authorities to close the beach requiring remediation interventions.

1. Introduction

Coastal zones are important natural areas with significant social and economic value. However, in spite of this remarkable role, shelf and beach environments are the final delivery sinks of various harmfulness materials produced in continental areas and transported by different agents to the coast (rivers, wind, acquifers, etc., Ambrose et al., 2019). In particular, heavy metals coming from industrial activities (Al-Shuely et al., 2009; Ramasamy et al., 2022), various PCB pollutants (Tolosa et al., 1995; Ragab et al., 2016; El Nemr and El-Sadaawy, 2016), and plastic materials (Reinold et al., 2020) often containing PCBs (e.g., beach plastic pellets, Karlsson et al., 2021), are the most ubiquitous pollutants delivered to coastal areas. These pollutants are imported into coastal environments through ordinary activities (industrial, mining, urban, touristic, fishing and mariculture activities), or by episodic incidents (e.g., accidental oil spills and shipwrecks) that represent hazardous threats to marine ecosystems and human health (see complete review in Fuller et al., 2022). In addition, scientists documented the illegal/uncontrolled direct dumping of large volumes of pollutants, often forming actual coastal landfills (Nicholls et al., 2021). These hazards are often the legacy of historical and recent fluid or solid waste disposal, on which the action of waves, tides, currents and global sea-level rise induce erosional processes, and the widespread dispersal of pollutants in shallow marine and beach environments (Goodman et al., 2020).

The occurrence of coastal landfills that contain historical or recent construction and demolition waste is widespread globally. Although such disposal is generally considered relatively safe, in fact debris coming from buildings, roads, railways, bridges, etc., constitute the fill (Osmani and Villoria-Sáez, 2019), and include glass, wood and steel, mortar, concrete, bricks and excavated soil (Noor et al., 2020). Typically, such construction and demolition waste contain variable quantities of Asbestos Cement Materials (ACM) deriving from corrugated roofing, slabs, pipes, tanks, flues, edile coating, floors, cement screeds and grouts (Obmiński, 2020). During the 20th century, Italy has been a leading asbestos producer, and one of the most important consumers in Western Europe (Virta, 2006). The Balangero mine (Piedmont Region), active from 1917 to 1985 (Silvestri et al., 2001), was the largest European Chrysotile quarry. Eternit and other companies built large industrial plants to produce asbestos cement (AC) from the earliest part of the 20th century. The first industrial site was built in 1907 in Casale Monferrato - Piedmont Region, later >50 factories were built in Italy from the 1930s until the end of the 1980s. Approximately75% of the ACMs in Italy have not been removed or reclaimed from the environment. The rate of increase for such operations of removal/recovery is about 1 % per year. Therefore, even by 2100 not all asbestos occurring in Italy will have been reclaimed (Angelini et al., 2021).

The ACMs containing asbestos are considered so highly dangerous to human health that such use of the mineral has been banned in many

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Fig. 1. A. The study area (Marechiaro bay) is located in the southern Mar Grande basin (northern Ionian Sea). Taranto city is limited by an extensive industrial center (North direction) which is directly connected with the Mar Grande and the Mar Piccolo marine basins (Google Earth 2022). B. Marechiaro beach is a traditional destination for the citizens of Taranto during summer season (photo taken on June 2020). C. The study area includes many environments with a significant naturalistic value (Google Earth 2022).

Western Countries (although still used/produced in Russia, China, India– *see* a complete list at http://www.ibasecretariat.org/). However, the ACMs often have been subject to illegal or improper dumping, driven by required complex and expensive disposal procedures (Paglietti et al., 2016; Liu et al., 2017), especially in countries affected by the prohibition. Frequently, the occurrence of dangerous fragments is globally reported along beaches by media and local authority alerts. (mainly in England, United States and *see* https://www.mesothelioma.com/blog/natural-disasters-disturb-asbestos-pose-health-threat/). Many coastal areas have been under clean-up or reclaimed. Moreover, the presence of deposits containing ACM asbestos in coastal marine areas has been reported in Italy (Bari, Bagnoli, Syracuse, Trieste).

Although asbestos pollution is a widespread environmental issue, relatedscientific literature is very rare. A few papers exist on reclamation procedures for coastal landfills containing ACMs (e.g., the capping methodologies suggested by Tomasicchio et al., 2010), but the erosion/transport/deposition dynamics of these materials along cliffs, beaches and shallow marine environments have not been analyzed. In particular, Tomasicchio et al. (2010) focused on a study area polluted by asbestos in the city of Bari, where the Fibronit company also produced pressure pipes. The production of asbestos cement pipes required a higher percentage of crocidolite than the production of plates, tanks or drain-pipes. Crocidolite, or blue asbestos, has a higher carcinogenic power than all types of asbestos (Hodgson and Darnton, 2000).

We applied an interdisciplinary (geomorphological, sedimentological, mineralogical) approach to analyze a coastal sector along the northern Ionian Sea (Mar Grande, Taranto, Southern Italy) where a large amount of construction and demolition wastes has been directly

Fig. 2. Location of the stratigraphic sections described and/or sampled along the cliff (1, 2 and 3) and unit areas for ACM fragments counting in the backshore sector (4, 5, 6, 7 and 8). Samples of ACM for x-ray and SEM analysis were collected on the cliff (1), at the base of the cliff (2) and in the backshore area (4, 6 and 8). Google Earth 2020.

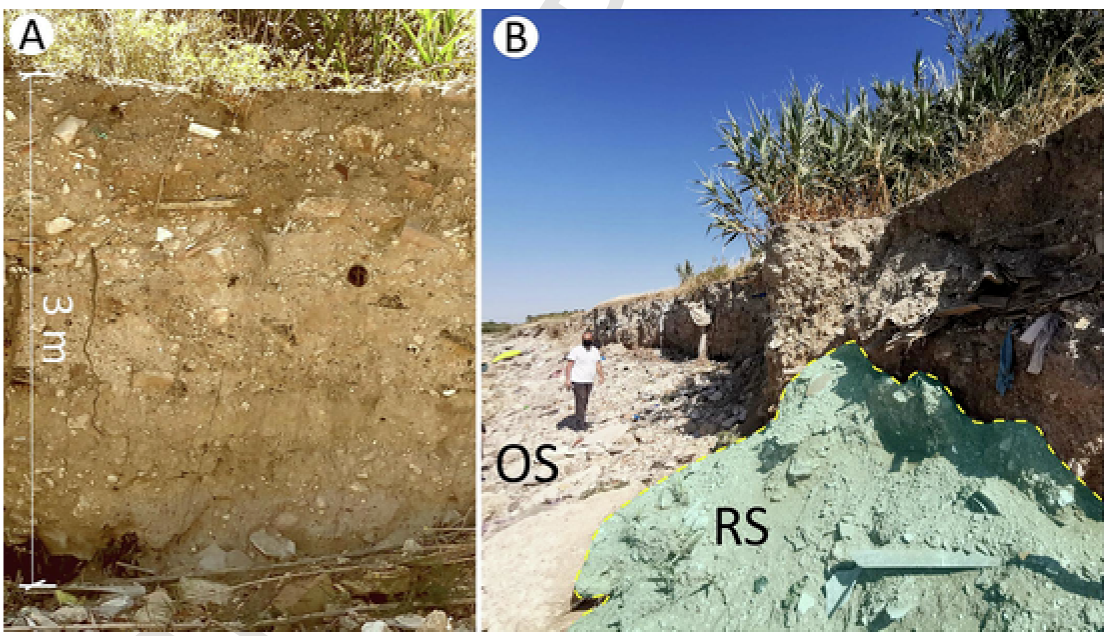

Fig. 3. The western portion of Marechiaro bay. A. The cliff has a sub-vertical shape, and the stratigraphic thickness reaches 3 m. The cliff deposits are stratified. B. The cliff is subject to slope instabilities. A recent landslide (RS) on the older debris deposits shows a flat and smooth upper surface induced by the action of storm waves (OS).

dumped at the coast. In this area, the marine erosional processes have induced the formation of a steep cliff, and the action of waves and littoral drift have contributed to the dispersal of these materials that include ACM.

This paper addresses the following objectives: -i) recognizing the geometry of the sedimentary bodies that contain construction and demolition wastes along the present-day cliff; -ii) dating of the different times of dumping actions; -iii) describing the erosional processes along the cliff; -iv) recognizing the presence of ACMs and describing them in terms of quantity, quality and physical state; -v) mapping the presence of ACMs fragments in the beaches adjacent to the cliff; -vi) showing the lateral variations of these fragments by long-shore transport; and -vii) evaluating the potential risk of exposurerelated to the presence of ACMs on beaches and proximal marine environments.

2. Study area

The city of Taranto, known as "the City of the Two Seas," is located on the Ionian Sea between the Mar Piccolo and Mar Grande marine basins (Fig. 1). The coastal area of Taranto is one of the most polluted sectors of the European Union. The industrial center (Fig. 1) is responsible for the production of about 92 % of the Italian dioxin (9 % of all European dioxin). The results of epidemiological studies conducted on the local population show a dramatic mortality excess, and an abnormal increase in congenital malformations in children which seem to be connected to all forms of industrial pollution (Zona et al., 2019). For these reasons, the Taranto area has been included in the list of Sites of National Interest (SIN - Law 426/1998 and Ministerial Decree of 10/01/2000, 1998). For the purposes of their remediation, the SIN is identifiable based on the quantity and hazard of the pollutants present, the im-

Fig. 4. The cliff-dumping deposits. A. A metric, massive dumped deposit (for the location, see point 3, Fig. 2). The graphic scale is 10 cm in length. B. Alternation of dumped deposits (for the location, see point 2, Fig. 2) with a different content of sandy matrix. The stratification is irregular, and the sedimentary bodies have a lenticular geometry with a scarce lateral continuity. The location of C and D figures is shown in light yellow. The graphic scale is 10 cm in length. C and D. Details of the upper portion of dumping deposits. A qualitative fragments classification with different origins is shown. In light green, the ACM fragments. Legend: A: asphalt; B: bitumen; C: cement and mortar; P: plastics; PW: plywood; T: tile (ceramics). Note that the type of man-made materials changes laterally in a few tens of centimeters. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

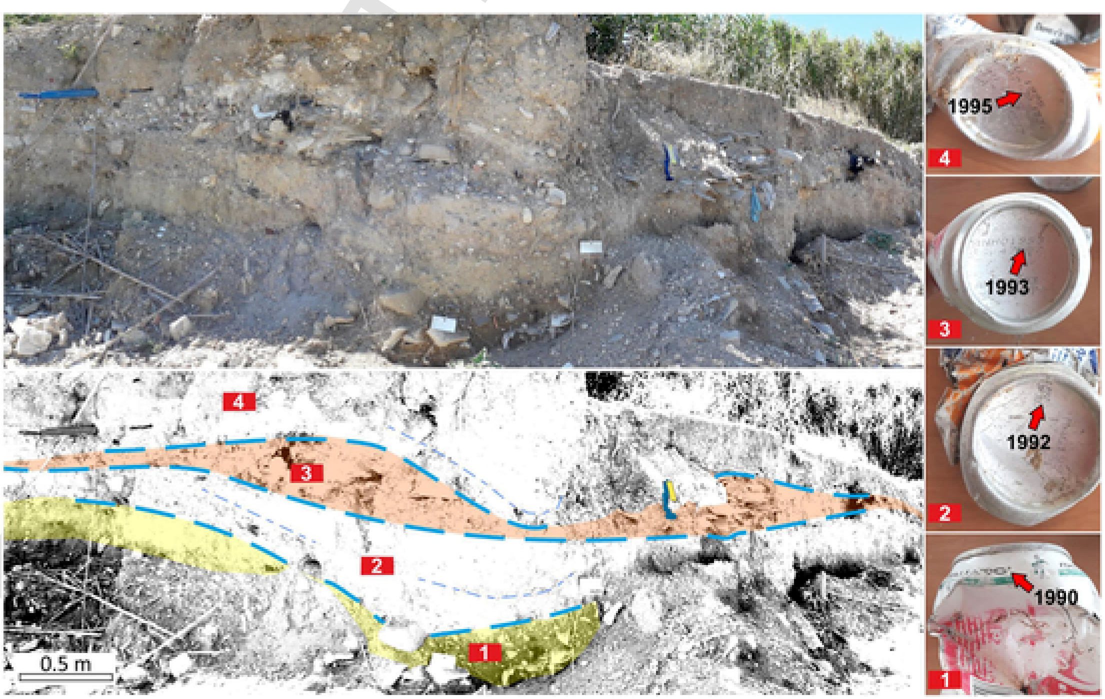

Fig. 5. The stratigraphy of the cliff in the eastern sector of Marechiaro bay. Four main dumping units were recognized. They show a clear prograding geometry with superposed and inclined sedimentary bodies migrating toward the sea. Note the presence of thick debris deposits at the base of the cliff. On the right, the drink cans used for dating analysis. All dumping operations were carried out during the 1990s.

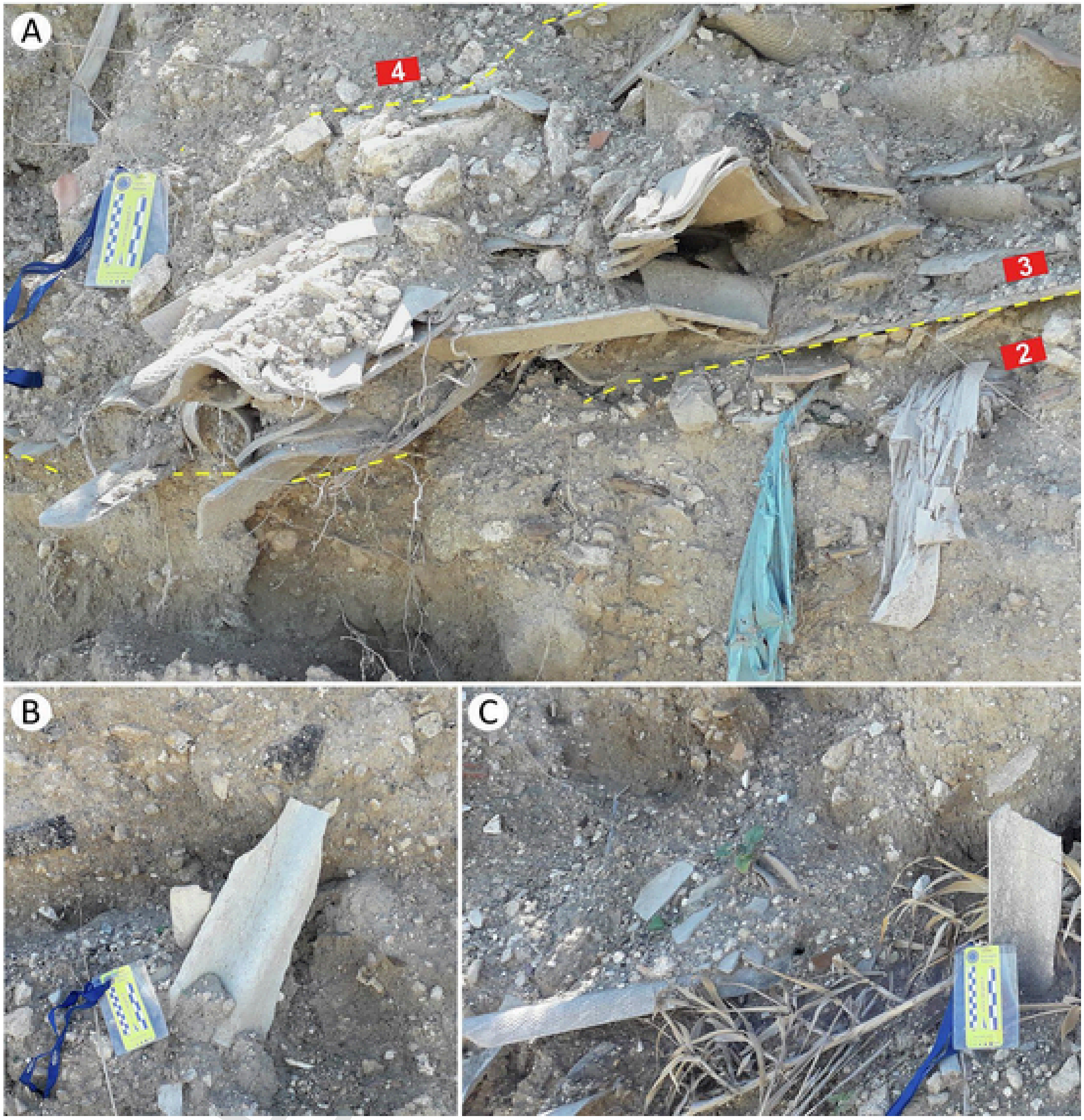

Fig. 6. A. Unit 3 contains large scale fragments of ACM. They are broken portions of roof corrugated tiles. Unit 2 and 4 seem to have no detectable fragments of ACM. B and C. Some details of the deposit at the base of the cliff. Abundant fragments of ACM with different dimension. Many AC tiles are in a vertical position. The graphic scale is 10 cm in height.

Fig. 7. A. Marechiaro beach is characterized by a narrow-emerged beach, small dunes and a localized lagoon. Remains of *Posidonia oceanica* occur in the shoreface and foreshore areas. A large seagrass area characterizes the sea bottom of the offshore transition sector; B. Low-elevation dunes, a narrow backshore area and a thick banquette in the foreshore sector typify the eastern part of this coastal area.

pact on the surrounding environment in terms of health and ecological risk, as well as damage to cultural heritage and environmental. In this case, the SIN covers a total area of 115 km^2 that includes the marine-coastal zones of the Mar Grande and Mar Piccolo basins; the sea surface extends for about 73.1 km^2, of which 51.1 km^2 are in the Mar Grande basin and 22 km^2 are in the Mar Piccolo basin. The Taranto seas (Mar Grande and Mar Piccolo basins) are deeply impacted by the presence of the largest steel industry in Europe (ex-Ilva), an ENI oil refinery, fishery facilities (Bracchi et al., 2016), and an Italian Navy port (Caroppo et al., 2012). Taranto is characterized by an important commercial and tourist port and an arsenal of the Italian Navy. This site has the productive characteristics of a shipyard with all the resulting impacts, which are

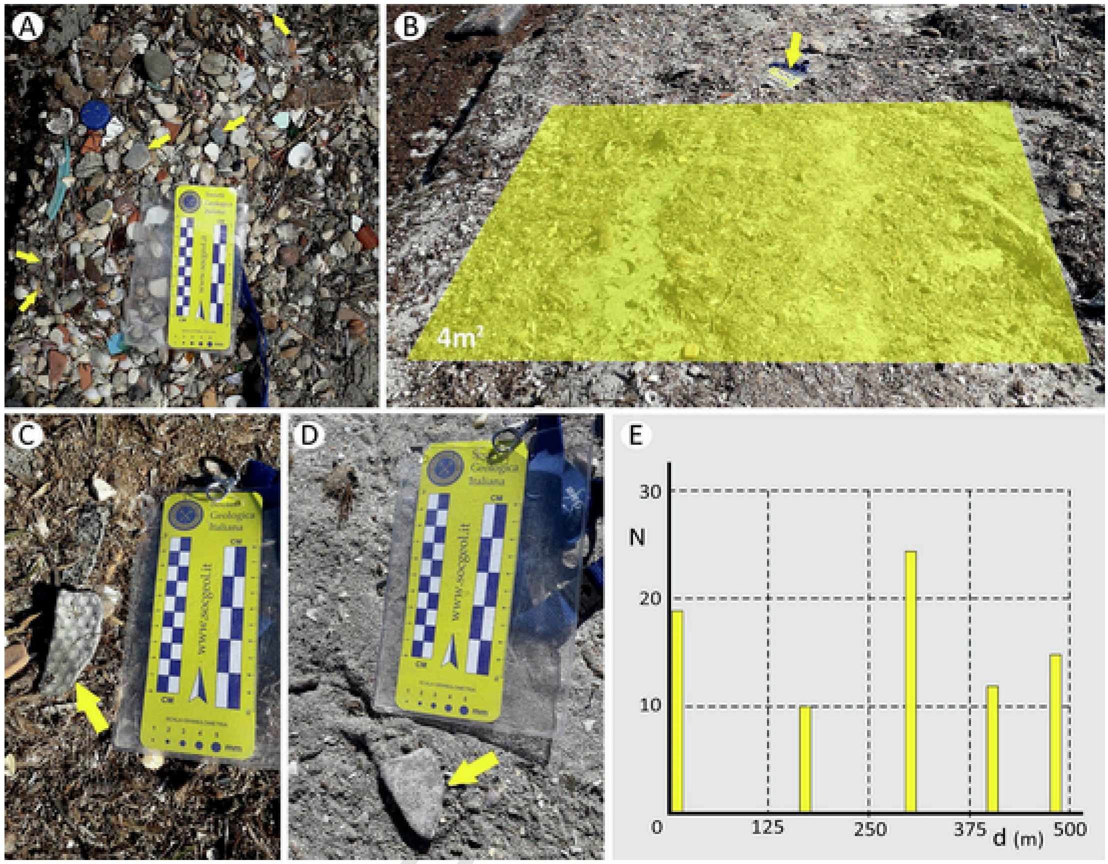

Fig. 8. The ACM fragments in the beach sector of Marechiaro bay. A. The backshore sediments are sand, and gravel made up of natural and man-made particles. *Posidonia oceanica* remains and shells of bivalve and gastropods are the main natural materials. Clasts of reddish bricks, whitish ceramic tiles and grey cement are also widespread. The ACM clasts are highlighted by the yellow arrows. B. The unit areas (see location in Fig. 2) used for the counting of ACM clasts is 4 m2. The yellow arrow indicates the graphic scale. C and D. Examples of ACM clasts (indicated by the yellow arrow). Only clasts with diameter > 2 cm have been considered. The graphic scale is 10 cm height. E. The W-E lateral variation of number of clasts (N) along the beach (d - distance from the first point located in the western sector of the beach, Fig. 2, points 4, 5, 6, 7 and 8). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

different from those of a simple port. Pollution is mainly concentrated in marine sediments as the final repository of litter from different origins and transport agents (Cardellicchio et al., 2007). The analysis of these polluted sediments shows a high content of organotin compounds (Massari et al., 2021) and concentrations of heavy metals such as Cd, Cu, Hg, Pb, Sn, Zn, etc. (Cotecchia et al., 2021; Rizzo et al., 2022) that are beyond the allowable limits of the National laws. Moreover, illegal dumping operations occur along these coastal areas. By 2022, >150 cars and 500 tons of other large-scale marine litter (tyres, motorcycles, drums with materials of unknown composition, washing machines, televisions, bathroom furniture, etc.) had been removed from the Mar Piccolo basin.

The Apulia beaches on the Adriatic and Ionian Seas are generally made up of mixed sands which include: siliciclastics, carbonate lithoclasts and bioclastic sands (Moretti et al., 2016; Van Loon et al., 2017; Lapietra et al., 2022a). However, Ionian beach sands are typically bioclastic with a reduced percentage of carbonate rock fragments coming from the erosion of limestone or calcarenite promontories (Milli et al., 2017; Lapietra et al., 2022b).

The San Vito promontory (Fig. 1), located between the Mar Grande basin and the Ionian Sea, represents the closest and traditional marine recreational area, in part because of the location far away from the Taranto Industrial and urban centers. In particular, Marechiaro bay (literally, "clear sea"), along the northern sector of San Vito area, has numerous pocket beaches that characterize the promontory (Fig. 1). The study-area beach is between two rocky headlands made up of Quaternary carbonates (MIS 5 calcarenite deposits – Lisco et al., 2016; Valenzano et al., 2018). Two submerged piers (a large submerged pier to the East and a smaller emerged one) were placed off of these bounding headlands (Figs. 1C and 2).

The Mar Grande basin coastal currents are conditioned by the morphology of the sea-bottom, and by diffraction processes (De Serio and Mossa, 2016) that induce a counterclockwise circulation (Gaeta et al., 2016) and the local East-directed littoral transport in the northern sectors of the San Vito promontory.

Marechiaro bay shows various physical elements and an unexpected biodiversity. The offshore transition sectors are covered by a large and dense *Posidonia oceanica* prairie (seagrass – Fig. 1C) which hosts many different benthic taxa (Rissoidea molluscs; and among the foraminifera: *Rosalina globularis* and *Cibicides lobatulus*) and the last individuals of *Pinna nobilis*, recently subjected to mass mortality processes in the Mediterranean Sea (Tiscar et al., 2022). The small dunes (Fig. 1C) are covered by robust and stable graminaceous herbs. In the retro-dune sector, a shallow lagoon (Fig. 1C) with abundant reeds and aquatic plants (and a population of migratory birds) exists. A narrow, N-S oriented fluvial incision has been obliterated by agricultural activities. This feature preserves the geological and biological characteristics of the so-called "Lame" which are the typical Apulian fluvial incisions with sub-vertical flanks and flat bottoms (Pieri, 1980).

3. Materials and methods

A preliminary description of the study area was carried out through geomorphological and sedimentological surveys along the cliff and

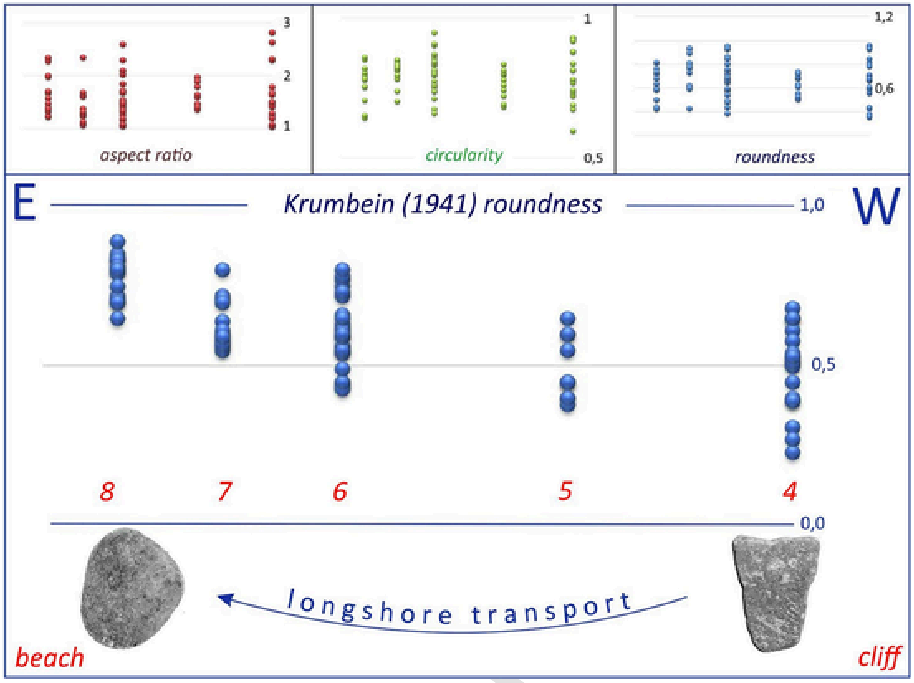

Fig. 9. Morphometric analysis. The graphs show the variation of the aspect ratio, circularity and roundness along the 5 sampling unit areas and the roundness calculated with the Krumbein (1941) comparative tables.

Table 1
Location, associations of asbestos minerals and their % by weight in the sampled ACMs.

Samples	Location (Fig. 2)	Asbestos minerals	% by weight
1	Cliff	Chrysotile, Crocidolite and Amosite	20.2
2	Base of the cliff debris	Chrysotile, Crocidolite and Amosite	32.3
4	Backshore	Chrysotile and Amosite	21.0
6	Backshore	Chrysotile, Crocidolite	24.5
8	Backshore	Chrysotile, Crocidolite and Amosite	25.1

backshore-foreshore sectors. A scuba-diving survey was conducted in the submerged area of the beach, from the shoreface to the offshore transition (5–6 m depth).

A detailed description of the stratigraphic succession, made up of dumped materials that crop out along the cliff, was carried out for three different points (sites 1, 2 and 3 – Fig. 2), a few tens of meters away from each other. Remains of commercial products were collected to approximate dates of the single stratigraphic dumping events. Five sampling sectors with a 4 m^2 area (points 4–8 in Fig. 2) were selected along the backshore (eastern sector of the study area), at the same distance from the coastline (about 2 m). The ACM fragments contained in the unit areas were photographed on site by using a white background and a graphic scale (80 ACM fragments with a minimum diameter of 0.02 m). High-resolution photos were selected to perform the morphometric analyses through Image J© software. In particular, four morphometric parameters were calculated: -1) the Circularity which describes the similarity of the particle shape with a circle; -2) the Aspect Ratio which defines the ratio between the particle length and its width; -3) the Roundness which highlights the difference between angular (breccia) or rounded (gravel) particles; and -4) the Solidity which describes the ratio between the area and the outline convex hull. The 2D analysis of the large fragments of AC is justified by their flat morphology; the measured thickness of the AC fragments can be considered negligible compared to the other two dimensions.

Five ACM fragment samples were collected from the following features: on the cliff (1 in Fig. 2), at the base of the cliff (2 in Fig. 2) and in the backshore areas (4, 6 and 8 in Fig. 2) for the x-ray and SEM analysis.

ACM Powder X-ray diffraction analysis (XRPD) was carried out with a Philips X'Pert Pro powder X-Ray diffractometer, employing as working conditions: Cu Ka radiation filtered by means of a curved graphite monochromator; 40 kV and 40 mA of power supply; divergence slit = 1°; anti-scatter slit = 0.5°; receiving slit = 0.2 mm; scan speed of 0.5° (2θ) per minute. The ACM samples, covered 30 nm graphite layer, were subjected to Scanning Electron Microscopy observations (SEM-EDS) (microscope EVO-50XVP LEO); microanalyses were achieved with an X-max (80 mm^2) Silicon drift Oxford detector supplied with a Super Atmosphere ThinWindow©. Petrographic analyses on sands were avoided due to the high risk of fibers dispersion during sampling, grain-size analysis and microscope observations.

In addition, remote sensing techniques were employed in order to evaluate the geomorphological changes of Marechiaro bay over the past fifty years. The landscape analysis of this coastal area was carried out with classical stereoscope techniques on aerial photos (historical series of Italian Military Geographic Institute of 1954, 1972 and 1978) and manually tracing the geomorphological elements. A comparison between aerial photos (IGM 1978) and present-day satellite images (Google Earth 2022) was also performed to preliminarily recognize the anthropic dumping activities, and to evaluate the approximate volume of the relative deposits. Furthermore, an analysis of the erosional and depositional dynamics of the coastal sector was investigated through satellite images (Google Earth from 2002 to 2020).

4. Results

4.1. The cliff of Marechiaro bay

The cliff of Marechiaro bay extends for about 500 m in length (Fig. 1C and 2) and has a sub-vertical shape (Fig. 3). It reaches a maximum of 3 m height in its central sector (Fig. 3A). The carbonate rocky substrate shows an irregular top which locally crops out at the sea level. A laterally continuous sedimentary body made up of the mixed man-made and natural debris occurs at the base of the cliff (OS in Fig. 3B). Debris deposits show a regularly sloped upper surface which extends from the cliff to the foreshore (OS in Fig. 3B); this regular top is frequently re-

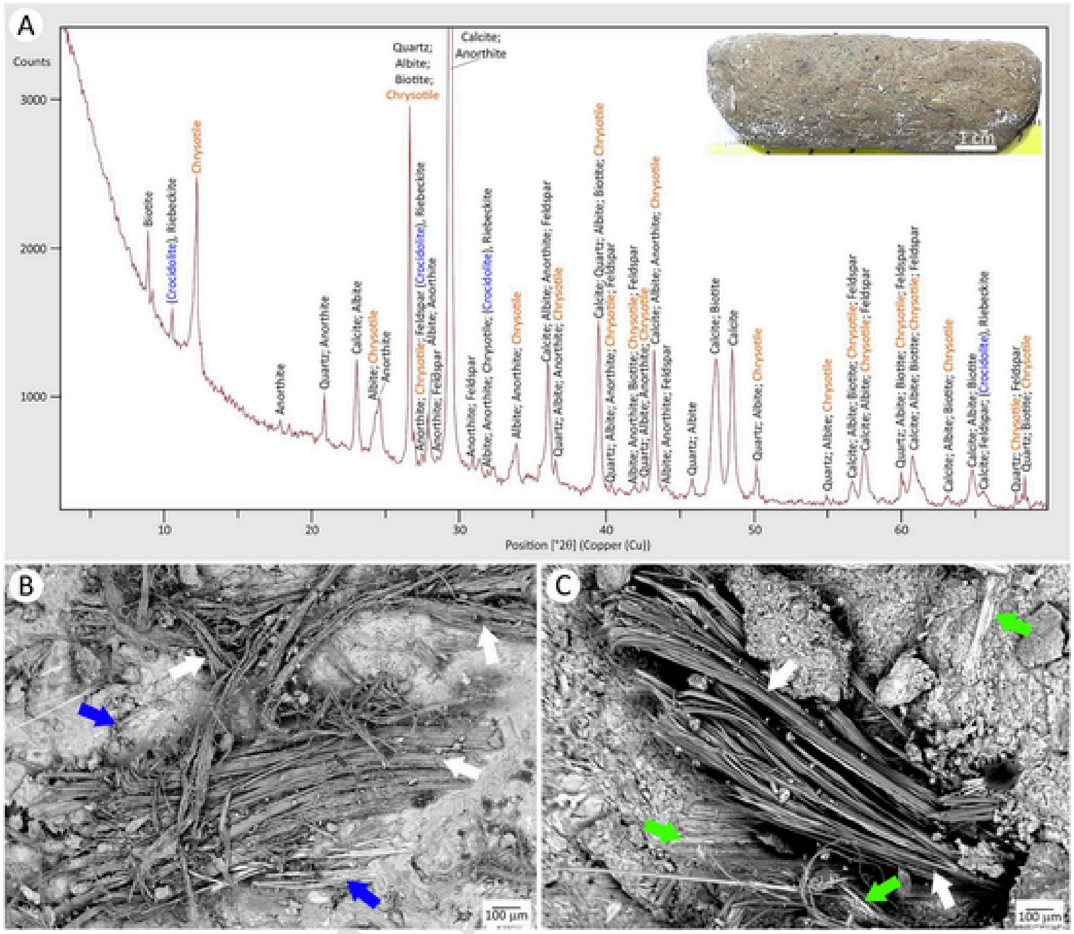

Fig. 10. Mineralogical analyses on ACM fragments collected in different points of Marechiaro bay. A: XRPD on sample 6 (see point 6 in Fig. 2): two asbestos minerals have been detected (Chrysotile and Crocidolite). B: Sample 6. SEM-BSE (back-scattered electrons) show the association between Chrysotile (white arrow) and Crocidolite (blue asbestos). C: Sample 4. SEM-BSE (back-scattered electrons) show the association between Chrysotile (white arrow) and Amosite (green arrows). In both cases, the SEM-BSE images show a cement matrix with scarce cohesion. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

worked by the wave action. The cliff seems to be unstable, and recent slide deposits (RS in Fig. 3B) occur on top of the older debris bodies. The instability is induced by storm-wave events which are recorded by the accumulation of abundant plant remains and rhizomescoming from the seagrass area, mollusk fragments and plastic materials at the cliff base. The cliff and debris deposits are composed of man-made materials, mostly coming from demolition work activities (Fig. 3).

4.1.1. *Stratigraphy of the cliff*

The man-made materials are clearly visible along the cliff, but their stratigraphic distribution is complex. The thickness varies from 0.2 m to 2 m along the western sector of the cliff. In some places (e.g., Fig. 4A – point 3 in Fig. 2), these deposits are characterized by a massive structure rather than a geometric organization in beds or sedimentary units. Moreover, a single 1.5 m thick bed occurs on top of a layer of coarser sediments. A thick rope crosses the whole deposit cropping out at different stratigraphic levels (Fig. 4A).

In the eastern part, the thickness of the cliff can reach 2–3 m and the clasts of man-made materials are organized in single beds, often showing a lenticular geometry (Fig. 4B). The contact between different sedimentary units is sharp, erosional, and shows a pseudo-channelized geometry. The lenticular beds have a low lateral continuity, suddenly disappearing along the cliff (Fig. 2B). The beds differ in grain-size, matrix-content and lithology (types of man-made material). The beds are made up of angular clasts with diameter > 2 mm (breccias), and they can be matrix-supported (para-breccia) or clast-supported (ortho–breccia), in terms of textural features (Fig. 4). The beds man-made materials contain cement, mortar, tiles in ceramics, wood and plywood, bitumen, road asphalt pavement, etc. (Fig. 4C and D), derived from demolition, construction, and renovation activities. Plastics are also widespread as well as various consumer products (aluminum shaving foam/deodorant/beverage cans, detergent containers, pieces of televisions and other fragments of unidentifiable objects). Lastly, many ACM fragments crop out in the upper portion of the succession (Fig. 4C and D).

In regard to the cross-shore stratigraphic section (point 1 in Fig. 2), dumped deposits show a prograding geometry (Fig. 5) toward the sea (N-NW) and a relative lateral continuity. The local stratigraphy of the cliff is represented by four separate units limited by different erosional surfaces (Fig. 5). Unit 1 is 0.7 m thick, and its base is not visible. This unit is made up of ortho-breccias with a low matrix content. Clasts are fragments of tiles, hollow bricks and carbonate rocks (limestones and calcarenites). Unit 2 is a 1.2 m thick para-breccia deposit with abundant yellowish sandy matrix. Clasts are mainly represented by cement fragments, but ceramic tiles and railway ballast (track ballast) are widespread. No fragments of ACM have been recognized in these units. On the contrary, unit 3 is 0.7 m thick and is made up of large ACM fragments. Moreover, unit 4 is a 1.3 m thick para-breccia deposit with an abundant grey silty and sandy matrix. The clasts are dispersed in the grey matrix, and they are represented by cement, mortar and rare fragments of ACM. The upper portion of this unit also shows traces of pedogenetic processes and a general brown colour (Fig. 5). This summary

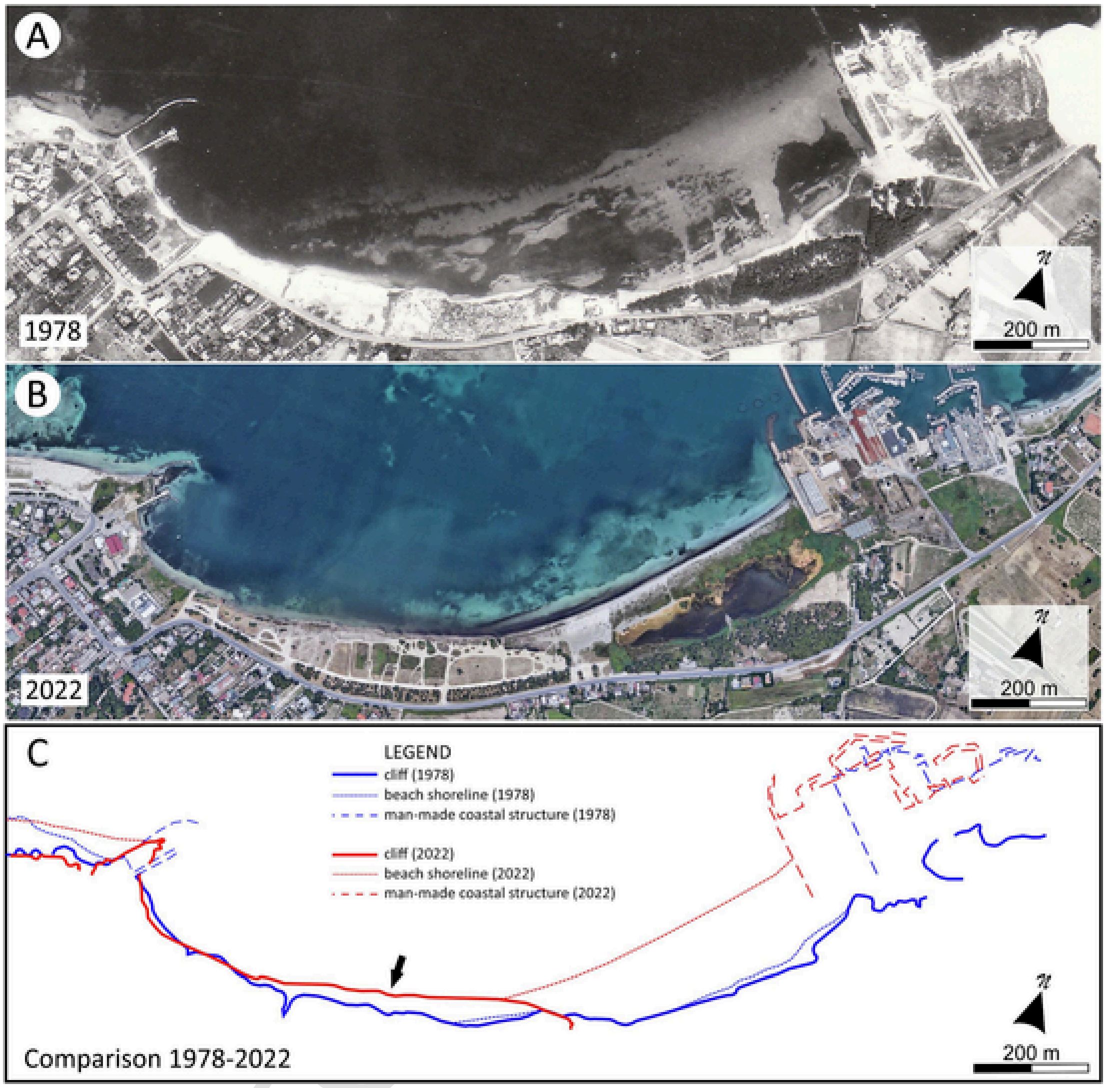

Fig. 11. Remote sensing analysis. A. Aerial photograph of the study area (IGM 1978); B. Satellite image of the study area (Google Earth 2022). C. A qualitative comparison of A and *B. major* changes affect the cliff sectors, beach shoreline, and man-made structures. Evidence for post-1978 coastal dumping operations is shown by the presence of an anomalous advancing cliff (indicated by the black arrow) at more recent time (2022). The shoreline also has prograded, and the small, localized beaches of 1978 have turned into a present-day well-developed sandy beach system.

description confirms the observations carried out in the eastern sector of the cliff (Fig. 4): the upper portion always contains fragments of ACM, whereas they seem particularly widespread in unit 3 (western sector – Fig. 5) where the ACMs are chiefly made up of roof corrugated tiles with their typical curved morphology (Fig. 6A). They are chipped, partially broken or in smaller fragments with diameters ranging from 20 to 2 cm (Fig. 6A). Numerous ACM fragments of large dimension (Fig. 6B and C) are also dispersed in other man-made materials with abundant matrix along the base of the cliff.

4.2. The beach of Marechiaro bay

The scuba diving survey shows that the seagrass begins below 5–6 m of water depth (the local base level of storm waves) and covers the offshore transition and deeper environments (Figs. 1C, 2 and 7A). The soft substrate is made up of fine-grained mixed sands with an abundant bioclastic content. The lower shoreface is nearly flat and contains fine-grained sands (Fig. 7A). This shoreface slope (upper shoreface) increases slightly as a result of the progressive increase in grain size toward the shoreline. The survey of the emerged beach sector shows gravel and coarse-grained sand along the foreshore covered by a thick *Posidonia oceanica* beach wrack (*Banquette*) (Fig. 3B). The backshore of Marechiaro beach is narrow, made up of gravel and coarse-grained sand, and limited by vegetated low-elevation dunes (Fig. 7A and B) with well-sorted medium-grained sands.

4.2.1. The ACM of the beach area

Sands and gravels of the foreshore and backshore sectors show a particular composition due to the natural and man-made particle origins (Fig. 8A). The natural organic materials are widespread (Fig. 8A) and are represented by bivalves, gastropods shells (or their fragments) and *Posidonia oceanica* remains (roots, rizhomas, and egagropoli). Man-made materials are also abundant, and composed mainly of red brick clasts, ceramic tile of different colors, grey cement, plastics, and glass (Fig. 8A). The ACM fragments are less common (Fig. 8A), but they regularly occur along the sandy-gravelly foreshore and backshore areas. To establish the lateral distribution of the ACM fragments, their number for unit area (4m^2 Fig. 8B) has been counted considering the clasts with the maximum diameter > 2 cm (Fig. 8C and D). An irregular variation of the number of clasts occurs along the beach (Fig. 8E) and seems to change randomly. A total of 80 ACM clasts were recognized in the 5-

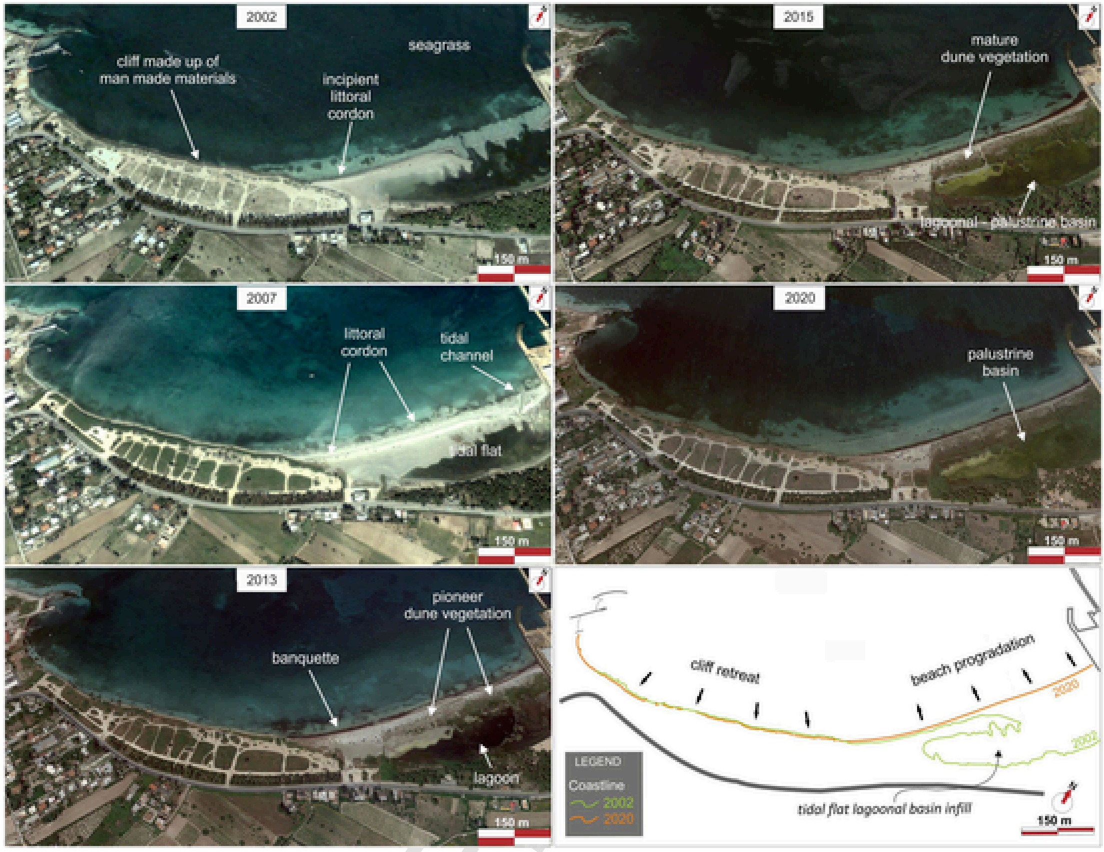

Fig. 12. Remote sensing on satellite images of the Marechiaro bay (Google Earth 2002–2020). Landscape and sedimentary environments in the eastern side of the bay record very fast changes.

unit areas corresponding to 4 clasts per m^2. Their morphology varies from angular or rounded to elongated or circular.

4.2.2. *Morphometric analysis on ACM clasts*

A simple image analysis was carried out on the 80 clasts from the unit areas of the beach sector (points 4, 5, 6, 7 and 8 – Fig. 2) to evaluate the lateral variation of the morphometric parameters. ImageJ software directly provides the morphometric parameters using photo binary images. Using these calculated parameters, it was possible to recognize a lateral variability (Fig. 9A), even though the data are scattered. Data dispersion depends on the final shape of the initial ACM fragments (random) shape. Using the Krumbein (1941) comparison classes, the geometrical system becomes easier (Cruz-Matìas et al., 2019) with a clear correlation (Fig. 9B). ACM clasts are transformed from angular clasts (similar to the breccias cropping out on the cliff) to well-rounded gravels through transport abrasion processes. As these ACM fractions, exposed to external agents and are eroded, break down into ever finer grain sizes, so their relative health risk increases.

4.3. *Mineralogical analysis on ACM clasts*

Five ACM samples were collected for mineralogical Powder X-ray diffraction analyses (PXRD) and Scanning Electron Microscopy observations (SEM-EDS): one on the cliff, one on the debris deposit located at the cliff base, and three along the beach of Marechiaro bay (respectively, points 1, 2, 4, 6, 8 – Fig. 2, Table 1).

The mineralogical analyses show the presence of the following asbestos minerals:

1. Chrysotile (serpentine asbestos, white asbestos), phyllosilicate group, having the following general crystal chemical formula: $Mg_6(Si_4O_{10})(OH)_8$.

2. Crocidolite (blue asbestos), the fibrous variety of the Riebeckite: group of double-chain inosilicates, having the following general crystal chemical formula: $Na_2(Fe^{+2}, Mg)_3Fe^{+3}{}_2[(Si_4O_{11})(OH)]_2$.

3. Amosite (brown asbestos), the fibrous variety of the amphibole Grunerite: group of double-chain inosilicates, having the following general crystal chemical formula: $(Fe_{+2}, Mg)_7[(Si_4O_{11})(OH)]_2$.

All samples contain Chrysotile as the main asbestos component (Fig. 10). Sample 6 also shows the presence of Crocidolite (Fig. 10A and B). Samples 1, 2 and 8 contain the association of Chrysotile with both the asbestos amphiboles (Crocidolite and Amosite), while sample 4 only shows the association Chrysotile and Amosite (Fig. 10C). The percentage of asbestos minerals in the samples (calculated with the XRPD analysis, Belluso, 2017) varies from a minimum of 20 % up to 32 %.

Lastly, SEM-BSE images (e.g., Fig. 10A and B) often highlight the presence of a cement matrix which is subject to a severe decay (crumbled or pulverized matrix).

4.4. *Remote sensing analysis*

Remote sensing analyses were carried out to hypothesize the approximate volume of dumped man-made materials and the evolution of Marechiaro bay during recent time.

The stereoscopic analysis of older aerial photos (IGM 1954, 1976 and 1978) shows the absence of detectable dumping operations during this period of time, but changes of landscape did occur in terms of new urbanization (civil housing and holidays villas) and agricultural activities. On the contrary, the comparison between the main morphological elements in the older aerial photos (mainly the cliff edge and the seashore – Fig. 11A) and the present-day landscape (2022 Google Earth images – Fig. 11B) highlighted the presence of dumping deposits (Fig. 4C). Fig. 4 shows a massive beach progradation during the last

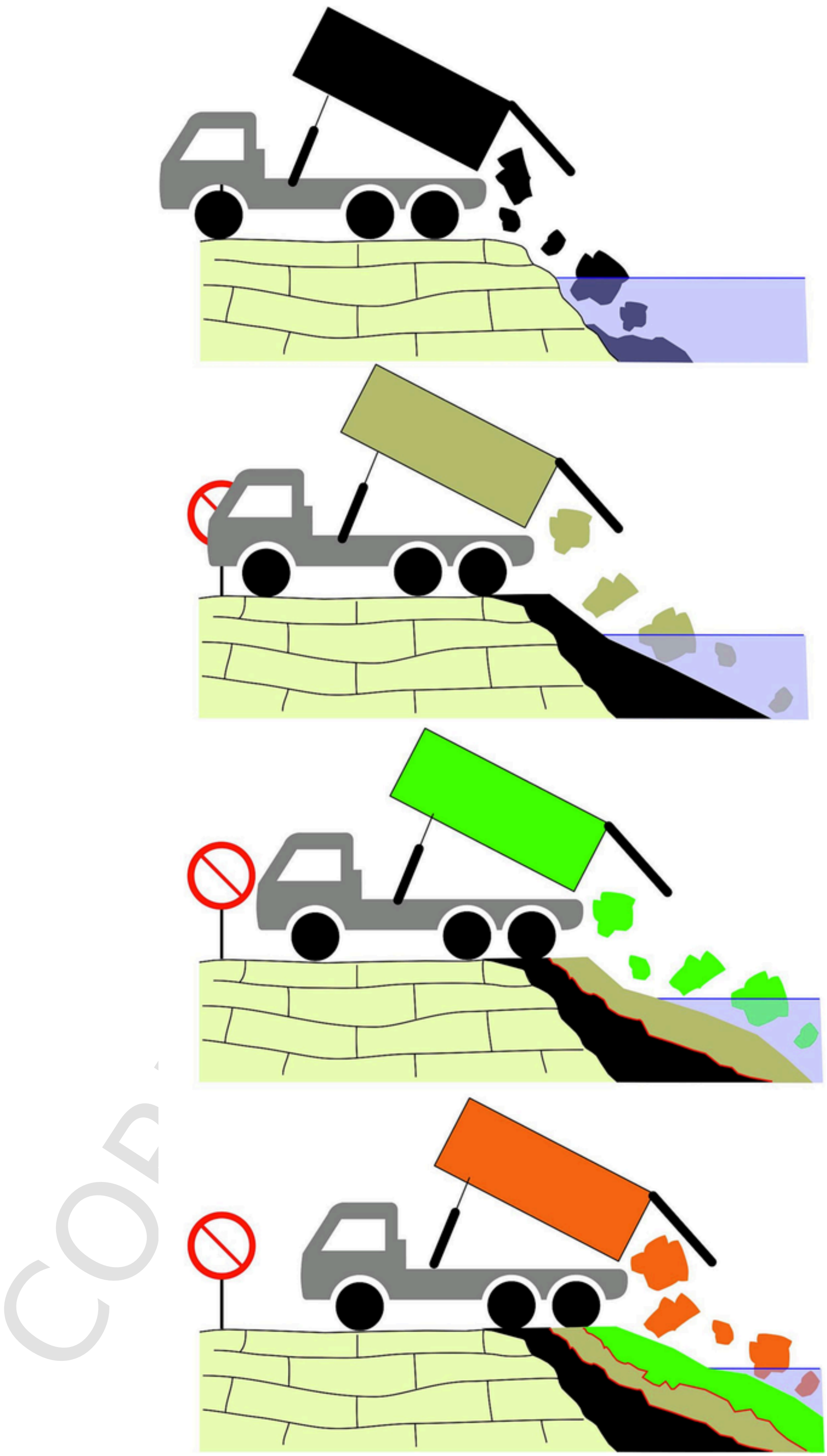

Fig. 13. Sketch of the origin for the occurrence of progradational geometries in the dumping units. This process reproduces the natural shifting of the shoreline in prograding beaches and delta sedimentary systems. Note the occurrence of irregular erosional surfaces (red line) between different sedimentary units as result of the dumping process. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

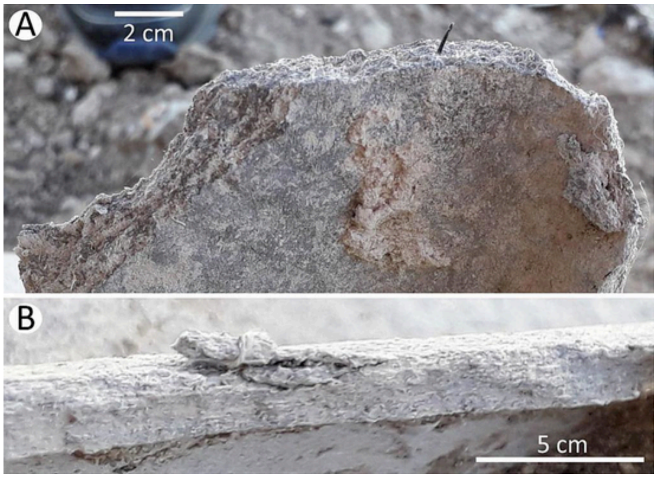

Fig. 14. The physical state of ACM cropping out on the cliff (A) and at the base of the slope debris. The macrophotos clearly show friable ACMs.

50 years, probably caused by the lateral expansion of the ship maintenance area located in the eastern sector of the study area (Fig. 4). Indeed, only large-scale dumping activities generally build an anomalous cliff "advancing" process (Fig. 11C).

This gradual process also can be described by analyzing the satellite images of the last twenty years (Google Earth 2002–2020 – Fig. 12). The retreat of the cliff is reflected by the associated rapid changes of the easternmost transitional environments.

Comparing the 2002 satellite image with the 1978 aerial photo, the presence of dumping materials is significant. Indeed, sand accumulation seems to begin along a man-made structure parallel to the coastline (probably, a submerged breakwater protection). By 2007, a continuous littoral cordon had produced a sort of tidal flat with a single tidal channel (Fig. 12). From 2013 to 2020 (Fig. 12), an actual beach system was established in this area. Dune formation followed the changes in the dominant vegetation, and a lagoonal-palustrine basin developed in the retro-dune sector. The alternation of lagoonal and palustrine conditions over time seems to correspond to slight variations in water depth, vegetation types and organic matter accumulation. The final sketch in Fig. 12 summarizes the main results of the satellite image analysis. A small cliff retreat in the western sector of the bay was accompanied by a rapid evolution (only twenty years) of the eastern sector in terms of landscape and sedimentary environments, inducing the infill of an original wide marine area by the formation and the progradation of a sandy beach.

5. Discussion

The multidisciplinary approach analyzed the complex issue of the ACMs illegally dumped in transitional environments which are typically highly dynamic in space and time (Arienzo et al., 2020).

The physical stratigraphy analysis of the cliff shows the geometry and lateral distribution of the man-made materials. In particular, the localized extent of single dumping deposits, the erosional surfaces between different units, and their progradational geometry is interpreted to be the result of repeated dumping operations carried out with dump trucks.

Generally, a progradational geometry is observed to nearshore sedimentary systems where deposition induces a regression with continuous shifting of the shoreline toward the sea (Bates and Jackson, 1987). Fig. 13 shows dumping operations that could produce geometries similar to the natural ones (for example, a prograding delta system). However, in this study case, the deposition is carried out through successive dumping operations directly into the sea and along a cliff made up of older man-made materials. Dumping processes form erosional (often channelized) surfaces between different man-made material deposits, inducing localized flows along the slope made up of previous deposits (as in natural marine debris flows, Niedoroda et al., 2006).

Dating analysis of the cliff outcrop deposits indicate that dumping occurred during the 1990s. The upper part of the cliff is characterized by the abundant occurrence of ACM, and these materials seem to have been suddenly deposited after 1992 (Fig. 5). These data agree with the introduction of Law n. 257/1992(Law 257/1992, 1992) which bans the use of asbestos. Rare clasts of ACM have been also found in older deposits, but they are randomly distributed in the dumping units. After 1992, the abundant presence of ACM becomes the result of illegal material disposal to avoid expensive operations which include removal, storage, encapsulation and finally confinement in appropriate sites (Paglietti et al., 2016; Liu et al., 2017).

Remote sensing analyses confirm the main dumping operations during 80's and 90's. Indeed, aerial photos before 1978 show the absence of man-made materials discarded along the cliff sector (Fig. 10). Furthermore, no evidence of new dumping operations has been detected after 2002 (Fig. 11).

Considering a constant thickness of 2.5 m and that the natural cliff was carved in the Quaternary calcarenites (Fig. 10A) in 1978, a rough volume quantification of the dumping deposit can be obtained by measuring the area comprised between the two cliff edges (1978–2022).

The volume is about 40,000 m^3. However, part of this material has been eroded and transported toward the adjacent beach (the Mar Grande basin circulation induces a long-shore current toward East; De Serio and Mossa, 2016; Mossa et al., 2020).

The mineralogical analyses confirm the nature of ACMs which is characterized by a variable content of asbestos minerals. This result indicates the presence of man-made materials coming from the demolition of buildings, roads etc., and belonging to different time of construction. High values could be associated with the cementitious matrix linked to the alteration and disintegration of the ACM fragments.

The beach investigation confirms the data collected in the adjacent cliff. Man-made materials of a different nature form the present-day beach. The natural component of transitional sands and gravels is strictly represented by the biological fragment component (mainly shells). Furthermore, starting from 2002, wide sectors of the original areas covered by the present-day lagoonal/palustrine environment have been filled by man-made materials (Fig. 11) increasing the ACMs distribution.

Moreover, the results connected with the morphometric analyses indicate that ACM clasts undergo rounding processes caused by transport abrasion along the coast. The friction and the impact with other materials induce a rapid rounding of ACM fragments because they have a lower hardness than other building materials (Adi Atmika et al., 2019). Major abrasion processes occur along the nearly flat surface of ACM clasts as results of their movement on a sandy substrate which is typical of the foreshore sectors (Stark et al., 2014). Moreover, the manufacture year and the physical/chemical state of ACMs clasts can be fundamental for their behavior in water and collision/abrasion processes. All these processes induce a dispersion of asbestos fibers in the beach environments increasing the risk of people's exposure.

Finally, most of the ACM fragments and clasts observed along the cliff and the beach of Marechiaro bay seem to be characterized by the so-called friable state (Laviano et al., 1997). The term "friable" is applied for any ACMs crushed, crumbled, pulverized, or turned into powder by hand. Note that the more friable asbestos-containing materials are, the more dangerous they are to human health (Ministerial Decree, 1994). Weathering of ACMs induces physical changes mainly in the cement matrix causing the asbestos fibers dispersion (Campopiano et al., 2009). SEM-BSE analysis describes the low physical state of ACM samples. The ACMs found along the cliff (Fig. 14A) and at its base (Fig. 14B) show a macroscale friable state, and therefore pose a high risk to human health. This susceptibility to release fibers is significantly higher in the clasts on the beach.

6. Conclusions

Several issues remain unsolved since the ban on Asbestos in Italy in 1992 (Law 257/1992, 1992)) and in the European Union (ECD 1999/77, 1999). In particular, asbestos removal and waste disposal are still an environmental/health emergency all over the world. Indeed, the high cost of removal and disposal operations and the lack of suitable State financings have favored the ACM illegal dumping into the environment (Angelini and Silvestri, 2022).

This study highlights a specific case problem connected to ACM dumping processes into the sea. Although asbestos has a high prevalence in Taranto, this coast has never been analyzed in detail for asbestos and most associated pollutants. In this respect, a part of our research focused on appropriate methodologies for analyzing ACM dynamics in shallow-marine environments. Results of these analyses highlight the need forinterdisciplinary approaches (e.g, geomorphological, sedimentological and mineralogical) to describe and manage such complex issues in a reliable way.

We identified several critical issues concerning the area of Marechiaro bay, which represents the final sink of hazardous materials, because of poor management and illegal dumping in the past. In addition, In addition, ACM fragments, deposited earlier, are now being deriving bye erosion from the cliff strata, adding to the total accumulation of hazardous ACM and related materials on an overcrowded, recreational beach, especially in summer seasons.

We have expressed the most important concerns of this study and encouraged the use of our results in management decisions. These research findings helped persuade the local authorities to immediately close the bay preventing access to the beach.

In addition, this study supports requests by decision makers and local authorities for remediation interventions. A project for reclamation and the use of this area as a coastal city park had already been funded by 2021.

CRediT authorship contribution statement

Stefania Lisco: Conceptualization, Writing- Original draft preparation, Investigation, Methodology, Data curation. **Isabella Lapietra**: Writing- Reviewing and Editing, Investigation, Data curation. **Rocco Laviano**: Data curation, Investigation, Validation, Writing- Reviewing and Editing. **Teresa Fracchiolla**: Data curation, Visualization. **Giuseppe Mastronuzzi**: Validation, Resource, Writing- Reviewing and Editing. Massimo Moretti: Writing- Original draft preparation, Investigation.

Uncited references

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.

Data availability

Data will be made available on request.

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