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Morpho-sedimentary dynamics of Torre Guaceto beach (Southern Adriatic Sea, Italy)

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Sandy beaches are the result of a dynamic interaction among physical conditions, biological processes and the anthropic impact (essentially linked to the natural resource direct or indirect exploitation). Monitoring the health state of coastal areas is a fundamental tool for land-use management. Moreover, integrated sedimentological studies with multidisciplinary methodologies are increasingly needed. This study aims to monitor the evolution of Torre Guaceto beach (Brindisi) over different seasons. The study area is part of a protected marine reserve characterised by a relatively slight human impact and a significant availability of previous data that allows us to observe the natural dynamic effects on the health state of the beach. The research was developed by adopting different techniques in order to investigate the foreshore and the shoreface sector of the beach. The geomorphological investigation, carried out with the terrestrial laser scanner and the optical total station, aimed to quantify the variations of sediment volume of the beach, while the sedimentological and petrographical analyses were conducted to define the sand textural and compositional characteristics throughout different sampling seasons; finally, Delft3d software was applied to analyse the effects of the dominant wave motion on the sedimentary dynamics.

Keywords. Coastal dynamics; pocket beach; sand beach; textural features; beach erosion; Southern Adriatic Sea.

List of symbols

M_z	Mean size
σ	Sorting
S_k	Skewness
K_G	Kurtosis
H_s	Significant wave height
T_s	Peak period

1. Introduction

Today, the conservation of coastal areas is significantly threatened by different hazards. Their natural exposure to extreme events, sea-level changes and uncontrolled human impact increase coast vulnerabilities and the attention of decision-makers to find sustainable solutions for their protection.

The understanding of processes that regulate erosion, transport and sedimentation mechanisms in coastal sectors concerns scientific research, economic, social interests and planning activities (National Research Council 1989; Kay and Alder 2002).

Within the earth sciences, the investigation of the beach environment represents a significant challenge (Schwartz 2005), particularly for sedimentologists (Greenwood and Davis 1984) and geomorphologists (Bird 2008). From a purely physical point of view, beaches represent complex sedimentary environments in which continental and marine processes interact at different space and time scales. Beaches can be defined as sedimentary bodies made up of sand, gravel or pebbles transported and deposited mainly by the action of waves, tides and currents. In the Mediterranean Sea, terrigenous sediments mainly come from delta deposits, by the erosion of cliffs or promontories whereas bioclastic components are represented by shells and fragments of the organisms that populate the proximal marine environments (Moretti *et al.* 2016; Pranzini 2019). Bioclasts derive from the continuous interactions between physical and biological processes and occur, with different percentage, in all coastal environments (Van Loon *et al.* 2017). Despite this, the bioclast percentage exponentially increases in some beaches developed along continental margins characterised by carbonate sedimentation.

Several studies have evidenced that beaches constitute extremely variable environments where different natural processes simultaneously act with human activities. For these reasons, from the 1960s onwards, because of the industrial development and growing urbanisation, the focus on sandy coastal erosion has led researchers and those involved in sustainable coastal management to increasingly implement methodologies focused on sedimentological, geomorphological and ecological aspects. Since the recognition of the sand textural parameters as a tool to evaluate the health state of the beach (Dal Cin 1969), the introduction of the concept of *equilibrium* profile (Dalrymple and Thompson 1977) for determining shoreline erosional rate and the role of dissipative and reflective characteristics (Wright *et al.* 1979) to classify the beach from a morphodynamic point of view (Wright and Short 1983, 1984; Masselink and Short 1993), the study of sandy beaches has experienced a significant development. Moreover, currently the knowledge of the relation between beach equilibrium and sea-level change represents a major challenge still raised in the recent past (Bruun 1962; Dubois 2002; Davidson-Arnott 2005; Lorenzo-Trueba and Ashton 2014; Scardino *et al.* 2020).

On this scientific basis, increasingly innovative techniques have been focused on the individual aspects of the earth sciences involved in the investigation of beach erosion. Detailed topographic surveys have been developed to study the shoreline variation through aerial photographs and satellite images (Ciavola *et al.* 2003; Gracia *et al.* 2005; Costas *et al.* 2006; Pranzini 2008; Anfuso *et al.* 2011; Nordstrom *et al.* 2015; Karkani *et al.* 2017). Within the geomorphological and engineering field modelling software has been elaborated to simulate the wave motion (Elias *et al.* 2000; Lesser *et al.* 2004) and its relation with sediment transport (Trouw *et al.* 2012; Fissel and Lin 2018); whereas sedimentological studies have been focused on grain-size distributions (Gao and Collins 1994; Guillén and Palanques 1996; Dawe 2001) and sediment trend analysis (Poizot *et al.* 2008).

Furthermore, despite the growing need to implement physical, sedimentological and biological data, few authors have considered the biological (Van Loon *et al.* 2017) and ecological approach (De Falco *et al.* 2003; Satta *et al.* 2013; Lisco *et al.* 2017) as a fundamental tool for coastal monitoring.

Recently, the implementation of different methodologies provides crucial information for sandy beaches nourishment interventions (Chiocci and La Monica 1999; Van der Salm and Unal 2003; Nicoletti *et al.* 2006; Onorati *et al.* 2007; Anfuso *et al.* 2011; Tortora 2020a, b) and leads to necessarily integrate the single techniques within an interdisciplinary approach. In addition, within the literature, still few studies gather all the aspects stated above or analyse them on a seasonal basis.

For this reason, we present a study focused on the application of a multidisciplinary approach aiming to analyse the morpho-sedimentary evolution of Torre Guaceto beach (Southern Italy). Currently, this beach forms a part of the most important marine-protected areas with high coastal dunes, rocky and sandy sea bottom and *Posidonia oceanica* bed. Unlike the surrounding areas, the beach is also characterised by a relatively slight anthropic impact, allowing us to analyse the real natural trends of seasonal changes by a sedimentological, petrographical and geomorphological point of view. Particularly, the aim of our research is figuring out the dynamics of

Torre Guaceto beach by gathering the following methodologies: (i) providing a textural and compositional analysis of beach sands, (ii) evaluating the morphological changes overtime and (iii) applying a numerical model to simulate the nearshore wave motion.

1.1 *Geological and geomorphological setting*

The Apulia region (Southern Italy) is characterised by 900 km of coastal sectors, which corresponds to 12% of the Italian littorals. Most of the economic and social activities are related to coastal areas and tourist facilities, which are concentrated in the marine localities. Among all the different coastal types, sandy beaches are the most common (>650 km in length) since cliffs and rocky shores only give one-fourth of the littoral sectors (Mastronuzzi *et al.* 2002). In the last few decades, despite the widely acclaimed concentration of tourism on sandy littorals, the significant economic development of many maritime localities has been seriously threatened by pervasive coastline retreats and, at present, coastal erosion is one of the most potential hazards for the economic development of the Apulia region. The specific literature contains recent studies on geomorphological and morphodynamic characteristics of the Apulian coast (Caldara *et al.* 1998; Mastronuzzi *et al.* 2002) and its relation with the urbanisation issue. Additional studies focused on vulnerable retreated areas (Caldara *et al.* 1998, 2012; Mastronuzzi *et al.* 2001, 2002; Annese *et al.* 2003; Milella *et al.* 2008; Moretti *et al.* 2016; Milli *et al.* 2017; Van Loon *et al.* 2017) by using classic surveys, innovative detection methodologies (Caldara *et al.* 2012; Infante *et al.* 2012; Mastronuzzi *et al.* 2018) or marine geophysics and morpho-bathymetric investigations (Annese *et al.* 2003; Mastronuzzi *et al.* 2012; De Giosa *et al.* 2019). Among these studies, a significant contribution about the characterisation of the Apulian coasts has been given by the research carried out on Alimini, Porto Cesareo, Torre Canne and Rosa Marina coasts (Falese *et al.* 2016). These sandy beaches represent the typical variability of Apulian littorals in terms of compositional sand, sedimentological features, morphodynamic characteristics and socio-economic relevance.

The beach of Torre Guaceto lies on a coastal sector located along the Adriatic coast of the Apulia region. The study area is part of the Southern Apennines orogenic system foreland and consists mainly of meso-cenozoic carbonate successions (Pieri *et al.* 1997; figure 1a). As a result of widespread karstic infiltration processes, the region contains few and intermittent rivers (mainly streams and torrents), which deliver limited quantities of sediments to littoral cells, and a general NW–SE alongshore current redistributes the terrigenous sediments towards the southern coastal areas coming from the Ofanto river (figure 1b).

The study area located in the north-western part of Torre Guaceto marine reserve is limited by two rocky promontories that draw an inlet whose shoreline stretches as far as 1 km. The south-eastern promontory named Punta Penna Grossa is represented by an outcrop of Lower Pleistocene shallow-water skeletal calcarenites (Calcarenite di Gravina), whereas north-westwards the beach is limited by an anthropic structure built in the first half of the 20th century. Therefore, the beach takes on the characteristics of a pocket beach (Mastronuzzi *et al.* 2017). Landwards, the beach is bordered by a dune belt that is recognisable all along the coast of Southern Apulia; it developed after the sea-level rise starting from its culmination that occurred about 7 ka ago (Mastronuzzi and Sansò 2002). The sea level continued to rise after this date at a rate of about 0.8 mm/year and only in the last two centuries, it accelerated up to a rate of about 1.8 mm/year as evidenced by the studies carried out on cores drilled in the Torre Guaceto area (Mastronuzzi *et al.* 2018). These cores have evidenced that in the lowermost part of the dune belt, a partially cemented sandy body (between 7 and 5 ka BP) occurred. It is followed upwards by a partially cemented or loose sandy unit interbedded with paleosol levels which were deposited during two different phases that occurred about 2500 ka BP and 700–500 years BP (Mastronuzzi and Sansò 2002). Currently, the state of conservation of the dune belt is significantly high and this is evidenced by their height (up to 9 m high), while erosion of the same is found in the sectors not sheltered by promontories, particularly in the southernmost sector of the beach.

1.2 *Seasonal wind and wave climate*

Wind and wave data about the Apulia region are provided by the Regional Coastal Plan (2012). In particular, the available historical series of wind data consist of records acquired in the period 1951–2005. Regarding the wind appearance

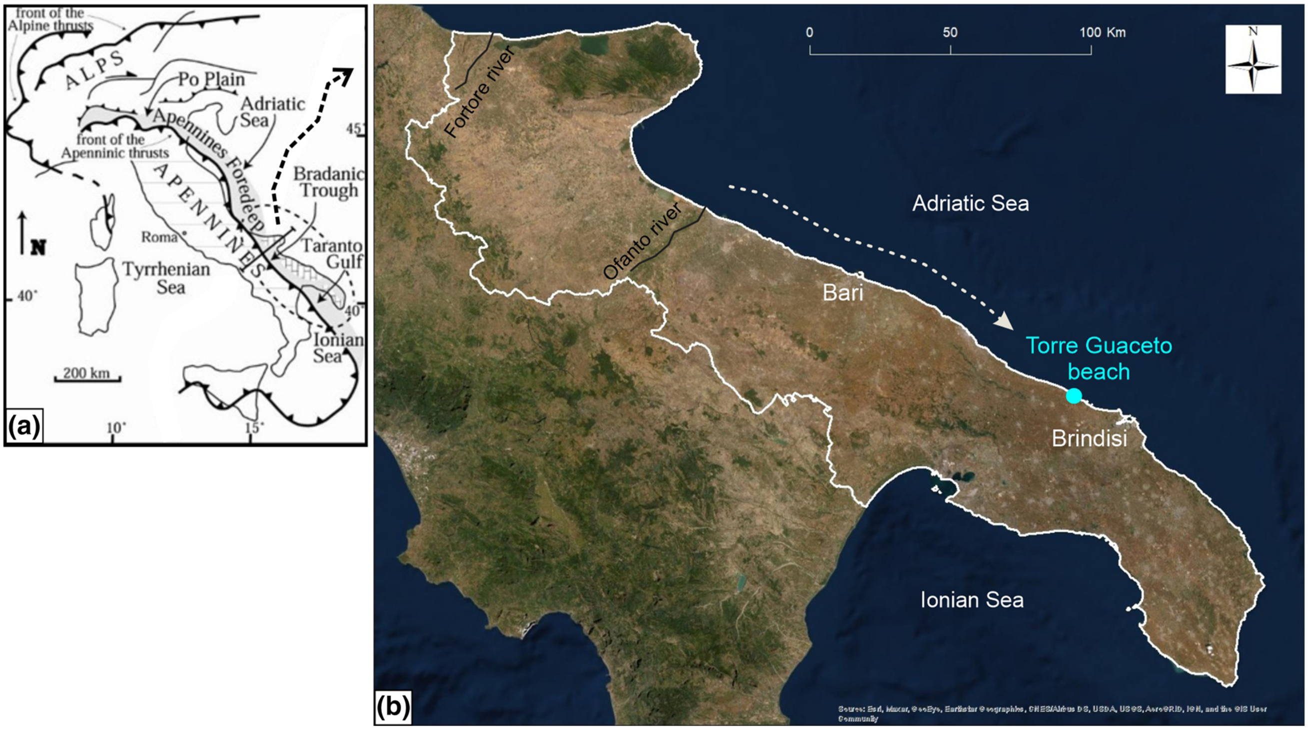

Figure 1. (**a**) Geological setting of Italian Peninsula (modified from Pieri *et al.* 1997) and (**b**) geographical location of the study area (light blue circle). The arrow indicates the general NW–SE alongshore current that transport sediments from the Ofanto river to the southernmost Adriatic coast.

frequency distribution, the greatest number of observations is related to winds from 330, 300 and 180°, whose percentage is around 12% during the winter season (figure 2a). According to the wind velocity values, winds with speed above 17 knots and with the highest frequencies are observed from 330 and 0° directions. In summer, the highest concentration of winds (around 22.9%) is observed from 330° and from the same direction, winds with the highest speed (>17 knots) are recorded (figure 2c).

The marine offshore climate of Torre Guaceto beach can be described by using data from the reconstruction of the meteorological climate of the Brindisi area. These data have been acquired by using the method of geographic transposition of wave data that is derived by the buoy moored off Monopoli in the period 1990–2005. Indeed, being the transverse sector of Monopoli the same of Brindisi (the two sites are remarkably close), the offshore climate can be considered similar (Barbone *et al.* 2013). As shown in figure 2(b), during winter season, wave directions are between 330° (16.79%) and 120° (15.36%). It is also observed that the highest frequency of appearance (22.15%) and highest significant wave heights (H_s between 3 and 4 m) derive from 0° direction.

In summer, the highest frequency of appearance (figure 2d) is due to storm events from 330° (32.52%) followed by waves from 120° (11.86%), 0° (9%) and 30° (5.54%). During this season, the significant wave heights exceeding 2 m are rarely recorded.

2. Materials and methods

2.1 *Topographic surveys*

The topography of the emerged beach was investigated through a terrestrial laser scanner (TLS) in order to construct three-dimensional (3D) elevation models and to quantify the changes over time. TLS allows acquiring the spatial coordinates of a large number of points by measuring the distance between the instrument and the object of study and by modelling point clouds to construct 3D elevation models. Two repeated survey campaigns were carried out during summer 2018 and summer 2019 by using a Riegl VZ-400 laser scanner with a theoretical range of 400 m. The instrumental accuracy of the TLS is ±0.003 m for 50 m. Due to the length of the beach, several scans were carried out from four stations with a distance of about 250 m and

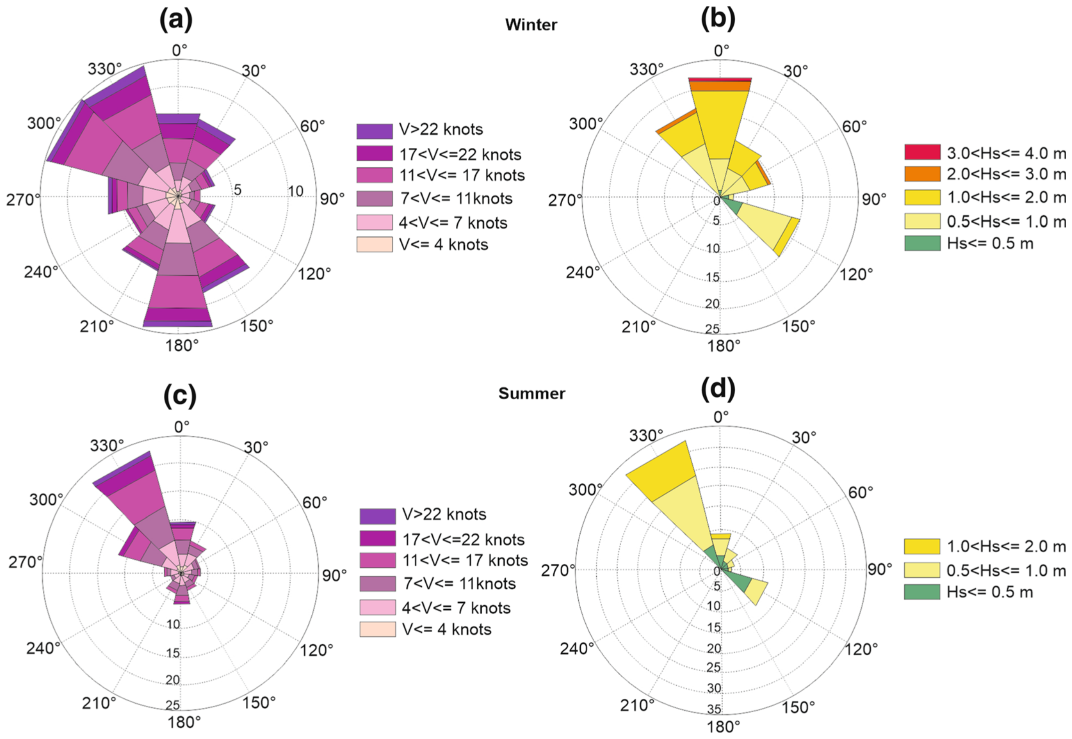

Figure 2. Wind directions and frequencies from Brindisi anemometric station during (**a**) winter and (**c**) summer season between 1951 and 2005. Directional distribution of the significant wave heights off Brindisi between 1990 and 2005 during (**b**) winter and (**d**) summer season (modified from PRC 2012).

four-point clouds deriving from the TLS survey were processed through several stages: (i) scans registration; (ii) multi-scan adjustment and georeferencing; (iii) 3D point cloud cleaning and (iv) triangulation (mesh) and digital terrestrial model (DTM) creation with a size cell of 50 cm. In particular, Riscan Pro and Cloud Compare software were used for point clouds processing, filtering and rasterisation, while the elevation correction, comparison of the two DTMs and the calculation of the volumes involved in the erosion and accumulation process were achieved with ArcMap © 10.1. Furthermore, due to the presence of different areas characterised by erosion and deposition, seven emerged beach profiles were extracted from the DTMs to investigate the morphology of the emerged beach and to calculate the amount of loss and gain material during the two campaigns.

In addition, two profile surveys by the use of the optical total station (OTS) Leica TS15 were performed in order to collect bathymetric information. The OTS comprises an electromagnetic distance measure instrument and electronic theodolite, which is also integrated with a computer storage system. The instrument allows to measure horizontal and vertical angles as well as sloping distance of object to the instrument. During the survey campaigns, the measurements were performed along two transects perpendicular to the coast in georeferenced points and by following the direction of the sampling transects for the purpose of comparing the profiles over time. About 20 bathymetric points were measured for each transect from the foreshore to 4 m depth (the maximum height of the distance measure instrument).

2.2 *Sampling*

From a sedimentological and compositional point of view, the sands were sampled in the middle part of the swash zone and across the shoreface (figure 3). Along the shoreline, the samples were spaced at around 100 m, while they were collected at each metre depth in the shoreface along two transects perpendicular to the coast from 1 to 6 m depth (the local storm-wave base in the Adriatic Sea) through diving techniques. In the shoreface, around 300 g of sand was collected between 0 and 2 cm depth down from the water–sediment interface by following the standard sampling procedure for marine sediments (Poppe *et al.* 2000).

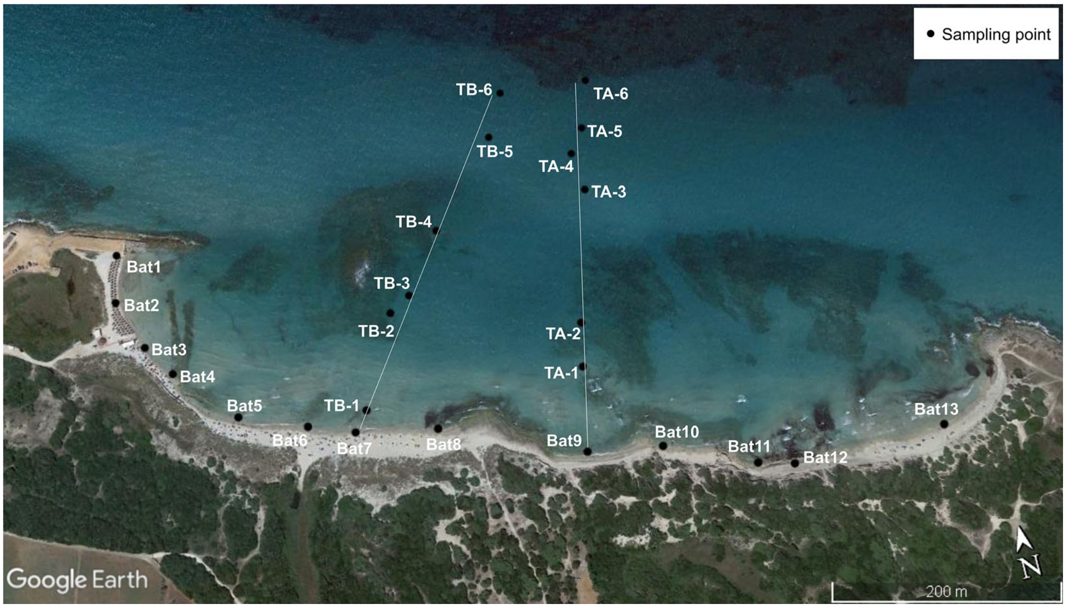

Figure 3. Location of the georeferenced sampling points. In the shoreface, the samples are located at each metre depth along the transects A (TA) and B (TB). In the foreshore, the samples were collected in the swash zone (Bat).

Since the samplings were carried out every 6 months, georeferenced points were used as collection points in the different seasonal campaigns. The utilisation of the same sites as sampling points, allows to compare the sediments from a granulometric and compositional point of view, and also to record the variations of sampling depth over winter and summer seasons. In total, 52 samples along the shoreline and 48 samples in the shoreface have been collected and analysed.

2.3 *Grain-size analyses*

The grain-size analyses were carried out by using the standard procedures provided by the American Society for Testing and Materials and the British Standard (ASTM). A set of ASTM sieves with meshes of ½ϕ from 2 mm to the minimum granulometric fraction (<0.125 mm) was used for the analyses.

The grain-size fractions with diameters <0.062 mm were excluded from the analyses because they were <1–2%. In the laboratory, the samples were dried in the oven at a temperature of 80° for 24 h and each individual sample was quartered and set in a sieve column. The grain-size sediments from 2.0 to 0.125 mm were sieved with the vibrating screen for a duration of 20 min. Subsequently, each held fraction was weighed and the results were processed with a specific Gradistat (v8) © application for Microsoft Excel, which yields distribution cumulative curves, histograms and statistically evaluate the following textural parameters: mean size (M_z), sorting (σ), skewness (S_k) and kurtosis (K_G).

2.4 *Compositional analysis and bioclastic component evaluation*

The most frequent grain size was investigated through a binocular optical microscope and the percentages of the main constituents of sands were evaluated to obtain quantitative and qualitative information in terms of petrographic composition. Since the investigation confirmed the presence of three main components, the sands were classified with the diagram proposed by Zuffa (1980, 1985), which provides the recognition of three main classes: carbonate lithoclasts (carbonate extrabasinal), bioclasts (carbonate intrabacinal) and non-carbonate grains (non-carbonate extrabasinal).

Furthermore, the bioclastic component of each sample was isolated by means of a set of tweezers from the rest and analysed in more detail. In this context, the unrecognisable bioclast fraction was separated from the whole and fragmented shells in order to define the unrecognisable percentage of each sample among three classes: 0–30, 31–60 and 61–90%. Successively, the whole and recognisable shells were divided on the base of their *Phylum* to provide a first classification. The class and genus

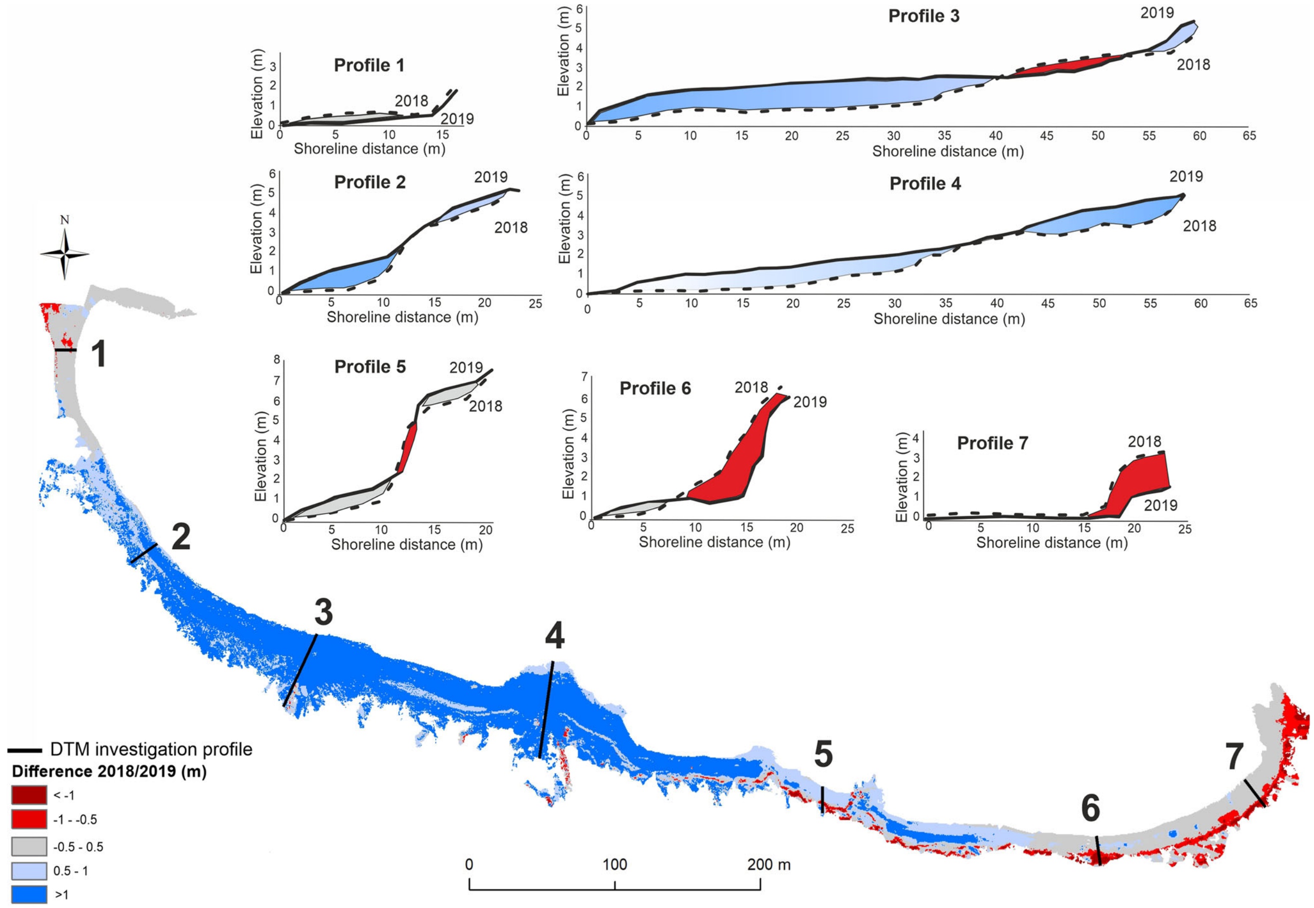

Figure 4. Raster difference between 2018 (dotted line) and 2019 (black line) with emerged beach profiles. The map shows erosion (red), accumulation (blue) and stable (grey) areas distribution. The elevation profiles, extracted by the DTMs, range from short and irregular profiles to those long and linear. The former refers to profiles characterised by sediment loss whereas the latter to accretion process.

of the shells were also evaluated in the case of foraminifera.

2.5 *Wave simulations and hydrodynamic model*

Software Delft3D was used to focus on the correlation between sedimentological parameters and wave processes. Delft3D is a flexible digital framework based on the third-generation spectral model simulating waves nearshore that accounts for refractive propagation, wind growth, bottom dissipation, depth-induced wave breaking and current dissipation. Therefore, Delft3D was applied to simulate the wave motion (WAVE module) and the calculation of hydrodynamic flows (FLOW module) to simulate the offshore wave features in the Adriatic Sea and to propagate them towards the coastline of Torre Guaceto.

The model setting was preceded by a series of operations needed for the correct and timely definition of the boundary conditions based on two main datasets: the bathymetry and the climatic information (waves and wind data). These data allow to analyse the hydrodynamic response of the surf-zone to the main meteorological events (Brambilla 2015). The bathymetric data were provided by the EMODnet website (https://portal.emodnet-bathymetry.eu/). The wave data were acquired from the Regional Coastal Plan (2006) in which the reconstruction of the meteorological climate of the Brindisi area has been carried out by using the method of geographic transposition of waveform data acquired by the buoy moored off Monopoli in the period 1990–2005. On the basis of the wave climate, we simulated two dominant directions: N0° direction with a significant wave height (H_s) of 4.46 m and a peak period (T_s) of 9.53 s and N330° direction with wave heights (H_s) of 4.34 m and a peak period (T_s) of 9.4 s. Fairweather conditions during the summer were estimated with $H_s = 0.93$ m and $T_s = 5.07$ s.

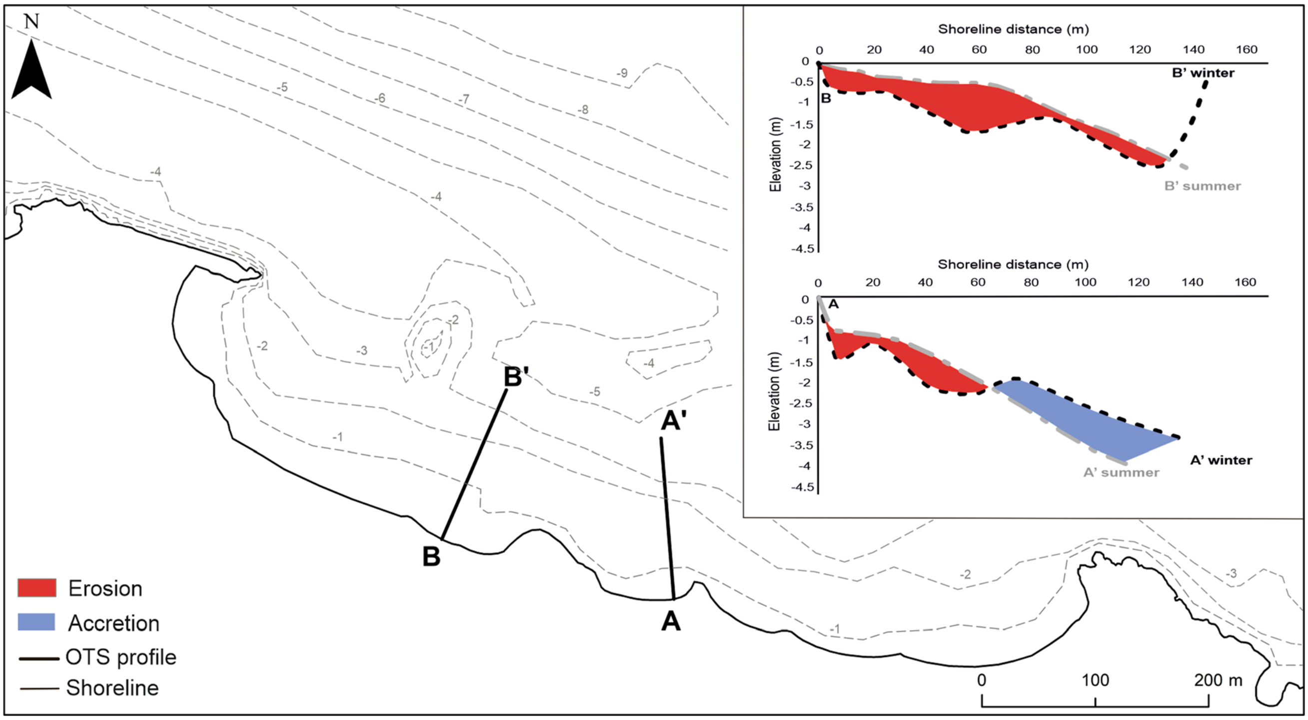

Figure 5. Map showing the location of the OTS investigation transects. On the top right are the graphs resulting from the measurements along BB′ and AA′ in summer and winter seasons. Both transects show a moderate sloping profile towards offshore and a significant erosion winter profile characterised by bars and troughs.

3. Results

3.1 *Geomorphological investigation*

The geomorphological investigation of the study area allows us to evaluate the macro scale and seasonal morpho-sedimentary variations of the beach over 1 year. The results are illustrated in the paragraph below and they are based on the different techniques applied to the emerged and the submerged sectors.

3.1.1 *Emerged beach*

Starting from the emerged sector, figure 4 shows the results deriving from the difference of two DTMs and the relative emerged profile comparisons. The map depicts five main different areas characterised by sand volume variations that occurred between 2018 and 2019. In particular, two range classes are representative of sediment loss (between <-1 and -0.5 m), two of accumulation zones (from 0.5 to >1 m) and one of unchanged condition (from -0.5 to 0.5 m).

Changes in the beach volumes are also highlighted by the extraction of 2018 and 2019 elevation transects, which range from short and irregular profiles to those long and linear. The former refers to profiles characterised by sediment loss whereas the latter to accretion processes.

As it is depicted in the picture, the northern–central sector of the beach falls into accumulation areas, especially in correspondence with profiles 2, 3 and 4. Along these transects, respectively 11.06, 36.75 and 43 m^3 of gain sediment is registered between 2018 and 2019. In the central–southern sector, the beach starts to thin out and it falls into stable and eroding areas. Particularly, the zone between profiles 5 and 6 is characterised by the most sediment loss that occurred mainly at the base of the dunes and at the first metres of the dune environment. Along transects 5, 10.65 m^3 of gain sediment and 1.5 m^3 of sediment loss are recorded during the measurement field surveys, while transect 6 is characterised by an accumulation of 2.34 m^3 and erosion of 14.76 m^3. Finally, profile 7 records 9.5 m^3 of material loss and falls into the most eroded areas of the beach.

3.1.2 *Submerged beach*

The changes in the shoreface beach profiles deriving from the OTS measurements during summer and winter seasons are shown in figure 5.

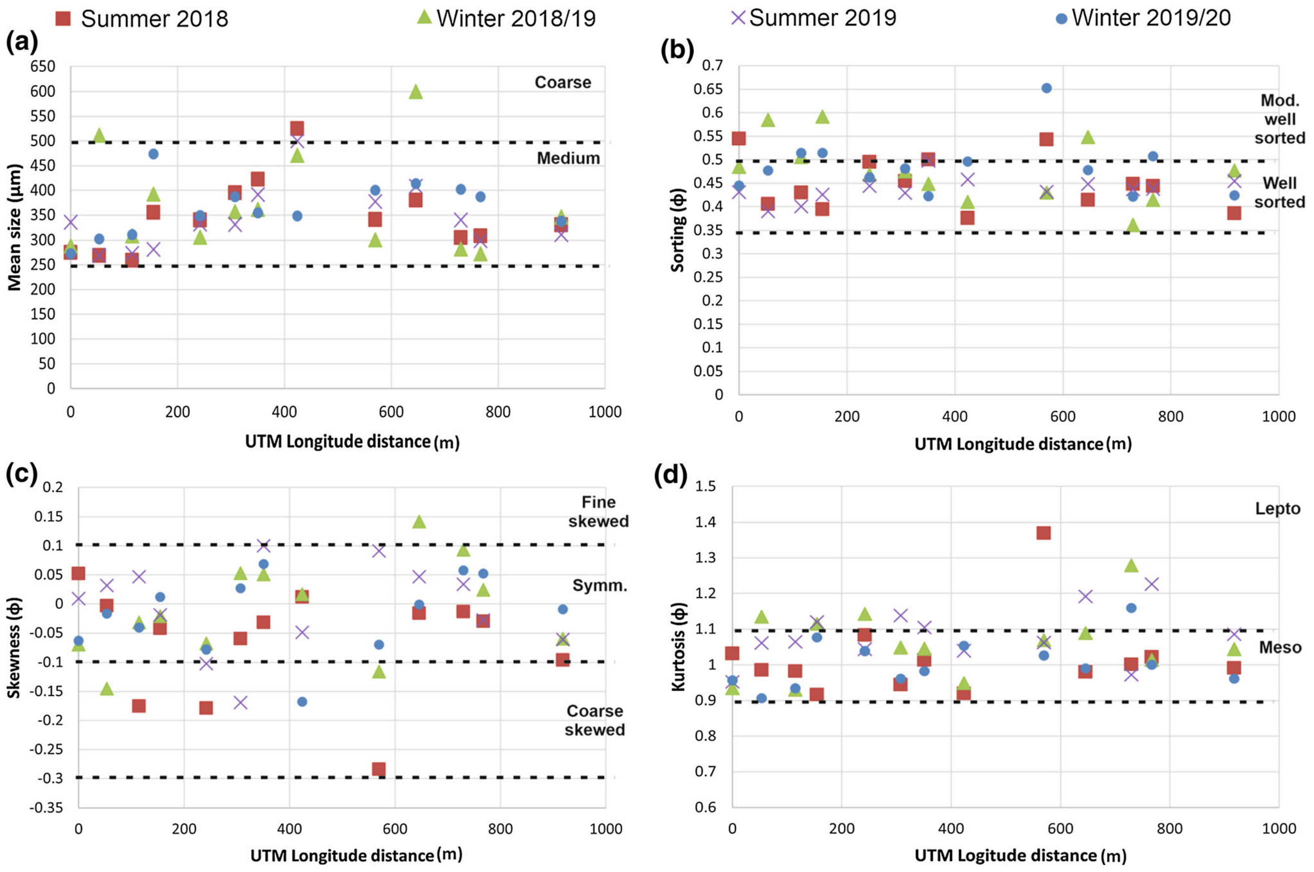

Figure 6. Foreshore sample parameter variations overtime. (**a**) M_z increases from the margins towards the central sector, (**b**) steady reduction of σ values (ϕ) in the central sector, (**c**) S_k ranges from symmetrical to negatively skewed curves and (**d**) K_G slightly increases from the northern to the southernmost sector of the beach.

Both summer profiles show a moderate sloping profile towards offshore and a significant erosional winter profile characterised by bars and troughs during winter. In particular, the winter profile AA′ is characterised by two bars located at 1.5 and 2 m depth and 34 m^3 of sediment loss were calculated between the two seasons.

Similarly, the winter profile BB′ shows two bars, respectively at 0.6 and 1.3 m depth, and it is followed by a significant elevation increase at 130 m from the shoreline due to the presence of a shoal. The amount of eroded sediment during the two seasons is 27.25 m^3, whereas the sediment accumulated is 21.5 m^3.

3.2 *Sand texture*

Besides the topographic surveys, the sand texture description is divided into two sections: the foreshore sample analysis which refers to the longshore investigation and the shoreface sample analysis for the cross-shore seasonal evolution of the beach.

3.2.1 *Foreshore samples*

Along the shoreline, samples mainly consist of well-sorted medium sands characterised by symmetrical skewness and mesokurtic curves. As shown in figure 6, the statistical parameters generally show linear trends. However, slight variations are observed among the samples.

The mean size, ranging between 258 and 600 μm, slightly decrease from the central sector towards the far end sectors of the beach and a steady sorting value reduction is also observed in the same direction varying between 0.36ϕ and 0.65ϕ. Skewness values range from symmetrical to negatively skewed curves. The only sample falling into the tail of the fine fraction range, refers to Bat10 collected in winter 2018/2019, which register the highest positive value (0.142ϕ). The kurtosis variation (figure 6d) shows an increasing trend along the shoreline and higher values are particularly reached in the southernmost area.

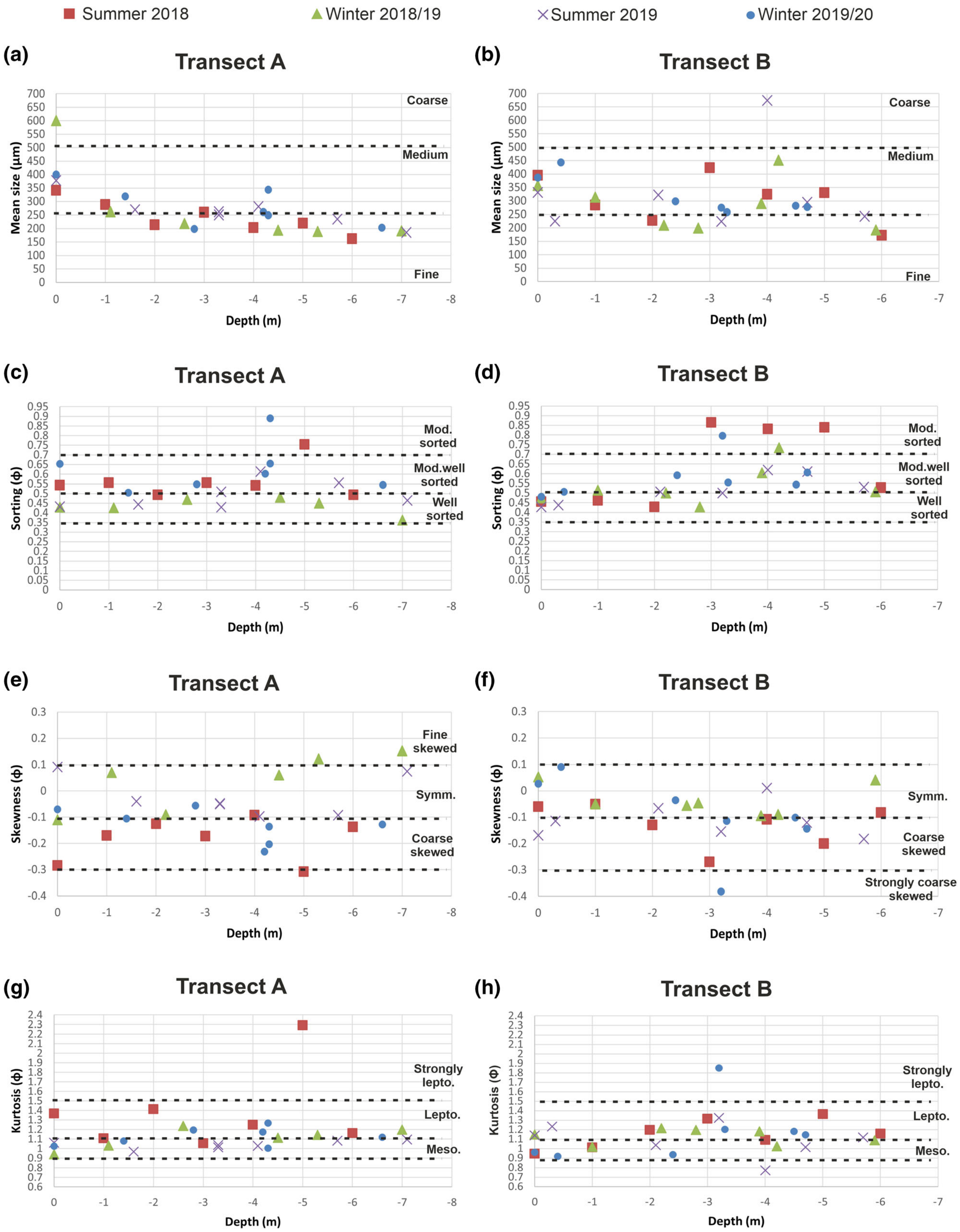

Figure 7. Cross-shore parameter variations along A and B sampling profiles. (**a** and **b**) M_z significantly decrease with water depth, (**c** and **d**) σ values (ϕ) increase between 3 and 5 m depth, (**e**) positive S_k in winter 2018/2019 and summer 2019, negative S_k in summer 2018 and winter 2019/2020, (**f**) almost all samples fall into a negative value range, (**g**) K_G highest values in summer 2018 and (**h**) K_G mainly characterised by leptokurtic and mesokurtic curves.

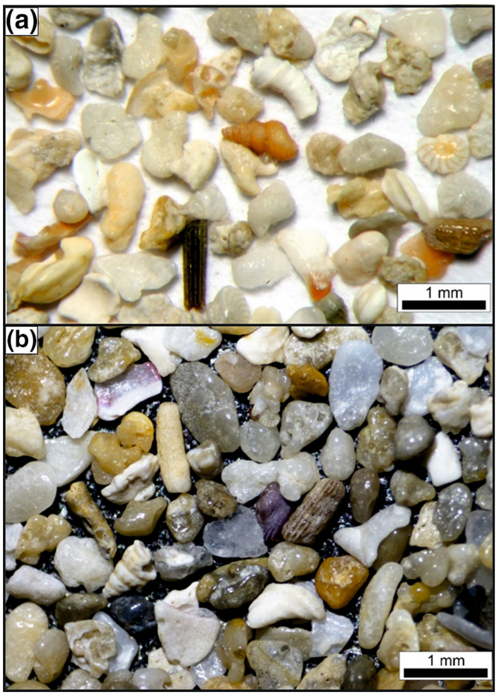

Figure 8. Petrographical features of the (**a**) foreshore and (**b**) shoreface of Torre Guaceto beach sands observed through an optical binocular microscope: Bivalvia fragments, benthic foraminifers, spines of echinoids, quartz grains and calcareous lithoclasts.

3.2.2 *Shoreface samples*

Medium–fine sands mainly characterise the shoreface samples collected along transect A. As shown in figure 7(a), the mean size significantly decreases with water depth. The sorting variation trend (figure 7c) ranges between 0.90ϕ and 0.75ϕ, showing a considerable increase between 3 and 5 m depth where the shoreface samples appear moderately (mod.) well sorted. The skewness variation (figure 7e) mainly highlights more positive values during winter 2018/2019 and summer 2019, than those characterising summer 2018 and the 2019/2020 winter, which show a coarser fraction.

Finally, the kurtosis shows a generally linear trend with depth (figure 7g) ranging from 0.96ϕ to 1.36ϕ. In this case, mainly leptokurtic (lepto.) curves represent the samples in summer 2018 and winter 2018/2019, while mesokurtic curves characterise the samples collected during summer 2019.

As well as transect 'A', mainly medium–fine sands characterise the samples collected along transect B. The mean size generally decreases with depth, but the highest values are observed between 3 and 5 m depth, where also a significant increase in sorting values is shown. In this case, the samples reach values around 0.89ϕ related to moderately sorted sand. Moreover, the samples collected during summer 2018 are characterised by tails of coarse material, whereas skewness equal to 0, prevail in winter 2018/2019, summer 2019 and winter 2019/2020. Mainly, leptokurtic and mesokurtic (meso.) curves represent the sediment sample distribution throughout all seasons.

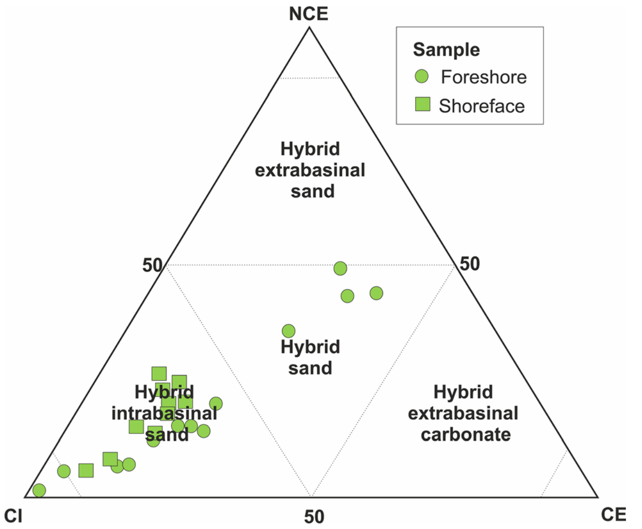

Figure 9. Composition-based classification of Torre Guaceto beach sands (CI, carbonate intrabasinal; CE, carbonate extrabasinal, NCE, non-carbonate extrabasinal).

3.3 *Classification of the beach sand and bioclasts evaluation*

The classification of sands containing carbonate and siliciclastic components refers to the definition of 'hybrid sands' (*sensu* Zuffa 1980) corresponding to the 'mixed sand' of Mount (1985) and the 'miscellaneous sand' of Pettijohn (1975). The petrographical results, deriving from the stereomicroscope analysis (figure 8), mainly define the sands of Torre Guaceto as 'hybrid intrabasinal sand'. However, a significant compositional variability is highlighted in the foreshore (figure 9), where the samples in the northern sector are richer in the bioclastic component than those of the southern sector.

3.3.1 *Foreshore bioclast variation*

The petrographic analyses carried out on the foreshore samples show a significant compositional difference between the sediments collected in the northern sector of the beach and the sands located in the southernmost part. In particular, a variation in the ratio between the

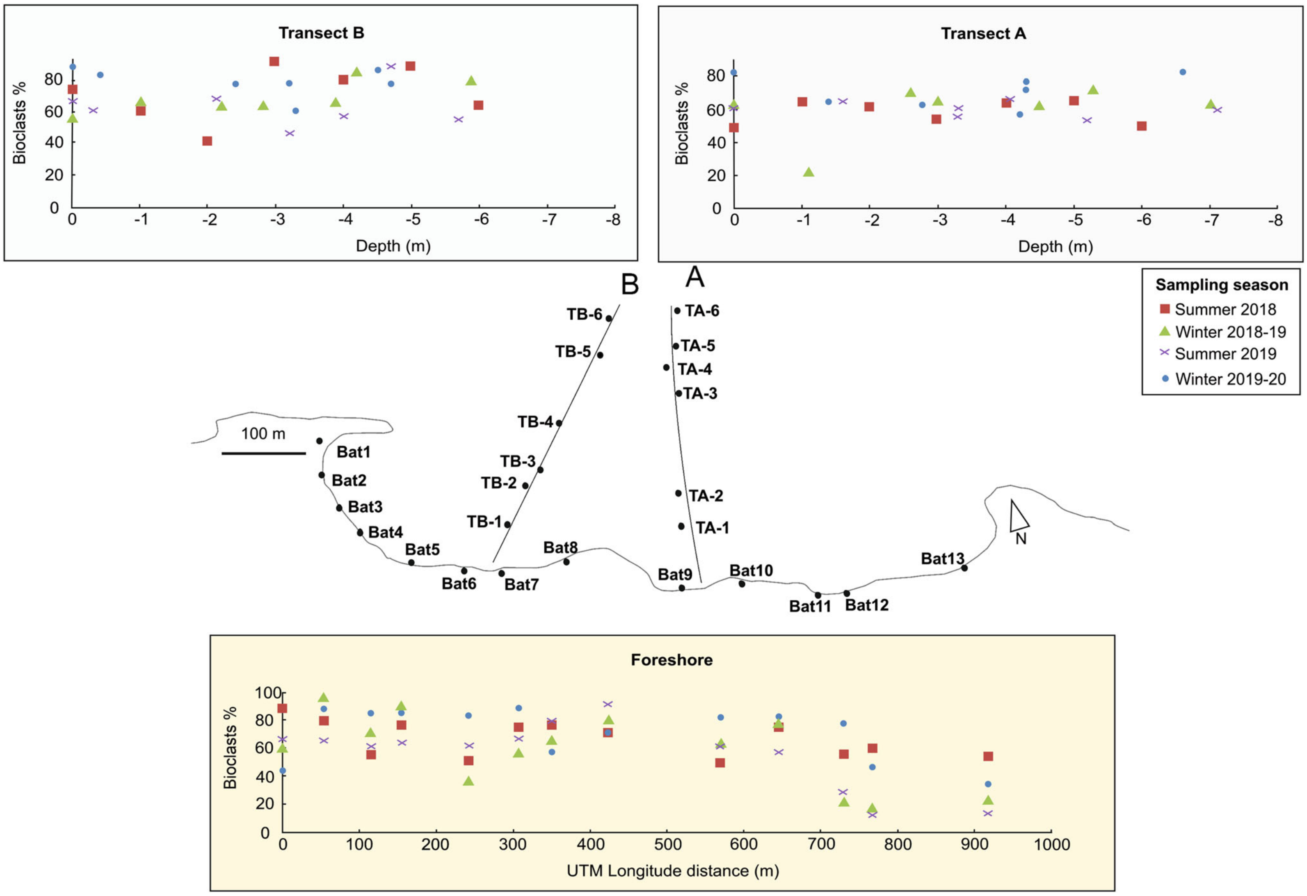

Figure 10. Location of the sampling points with the bioclast variations over time. Along the shoreline, the samples move from sands containing 80% of bioclasts in the northern sector of the beach to mainly siliciclastic sands in the southernmost part (<40% of bioclasts). In the shoreface, the percentage of bioclasts shows a linear trend along transect ‘A’, while transect ‘B’ depicts a steady increase towards higher depths (between 3 and 5 m depth).

bioclastic and the siliciclastic components is observed. Following the longshore direction from northern to southern sectors, the samples move from sands containing 80% of bioclasts to mainly siliciclastic sands characterised by an average percentage of bioclasts lower than 40% (figure 10). In addition, within the bioclastic component, we observe whole or fragmented shells of Mollusca (Gastropoda, Bivalvia, Polyplacophora); Foraminifera (in particular, the Globothalamea class characterised by *Elphidium* spp., *Rosalina* spp., *Ammonia* spp., *Globigerina* spp.; the Tubothalamea class including *Peneroplis* spp. are found; *Sorites* spp., *Quinqueloculina* spp. and Rotaliata class composed of *Bolivina* spp. genus); Echinodermata; Bryozoa; Rodophyta and Porifera.

3.3.2 *Shoreface bioclast variation*

The samples collected in the shoreface show slight variations in terms of petrographical composition. As well as the central–northern sector of the beach, they are characterised by high percentages of the bioclastic components which include the presence of foraminifers, spines and plates of echinoids, fragments of molluscs, bryozoans, red branched algae, spicules of sponges and fragments of arthropods. In addition, as shown in figure 10, the percentage of bioclasts is constant along transect ‘A’ (around 60%), while transect ‘B’ is represented by a steady increase towards higher depths. The latter also depicts a higher content of bioclasts than transect A.

3.4 *Model application*

The six models in figure 11 represent the variations of directional vectors, wave heights and dissipation along Torre Guaceto beach during extreme events in winter and summer seasons. Regarding the modelling derived from the N0° direction of the winter season, the wave height values vary from 0.2 m along the shoreline to 4 m in the offshore

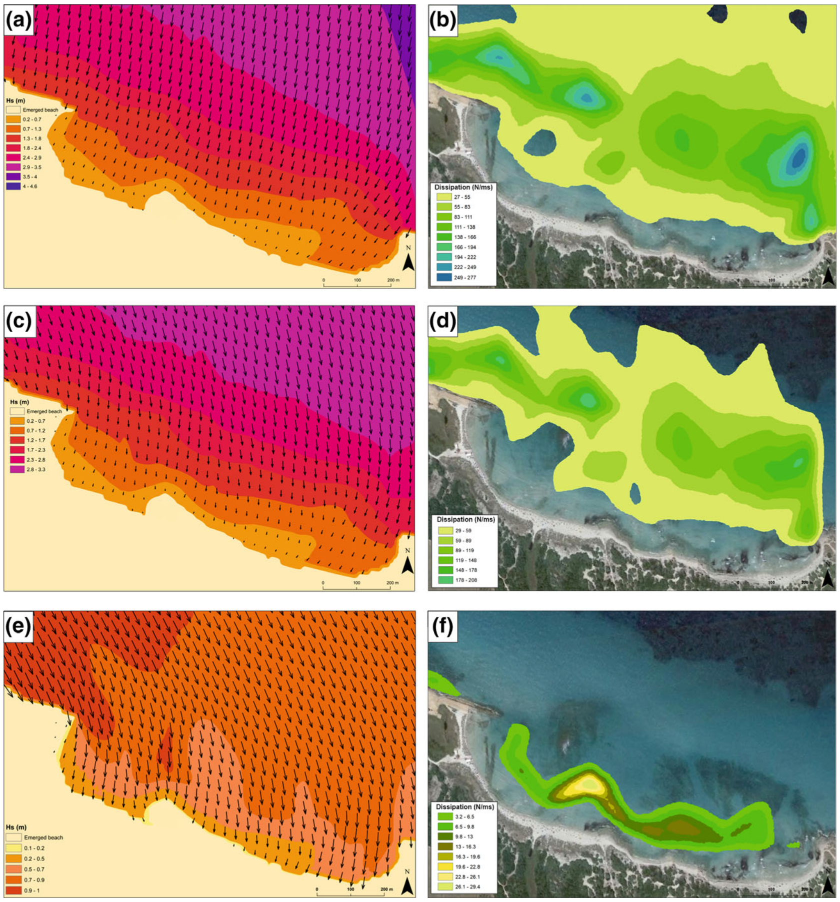

Figure 11. Maps showing the Delft3D simulation models of Torre Guaceto beach. (**a**) Directional vectors and wave heights for N0° direction during the winter season, (**b**) wave dissipation for N0° direction during the winter season, (**c**) directional vectors and wave heights for N330° direction during the winter season, (**d**) wave dissipation for N330° direction during the winter season, (**e**) directional vectors and wave heights for N330° direction during the summer season and (**f**) wave dissipation for N330° direction during the summer season.

areas. As it is shown in figure 11(a), the southernmost part of the beach is characterised by higher wave heights than the northern sector. In addition, following the direction of the vectors, there is a slight longshore transport from the south to the north of the beach. The dissipation (figure 11b) varies between 40 and 280 N/ms and highlights a large amount of wave transformation, especially, outside the bay. Similar conditions occur also in the winter season with extreme events in N330° direction, when the wave heights vary between 0.2 and 3.3 m (figure 11c) and the dissipation varies from 43 and 301 N/ms. During the summer season, the wave heights considerably decrease varying between 0.1 and 1 m (figure 11e) and the energy dissipation zone moves closer to the coast and inside the bay (figure 11f).

The dissipation models highlight a significant relationship between the geology of the area and the wave motion energy reduction. During the winter season, the rocky sea bottom, located between 2 and 5 m depth causes the wave energy loss and induces dissipation. Generally, this condition occurs when nourishment interventions are located along the coastline, but in this case study, it is a natural result of the geological setting of the area (figure 12). Moreover, part of the sediment transport derives from the offshore and there is a slight longshore transport from the south to the north.

4. Discussion

The recognised textural and compositional variations of Torre Guaceto beach can be attributable to the dynamics of the beach (figure 13). As previously defined, Torre Guaceto is a pocket beach, a stretch of coastline limited by two promontories and whose sediment transport takes place within the bay itself and with the offshore. Important information about the general sediment transport system can be

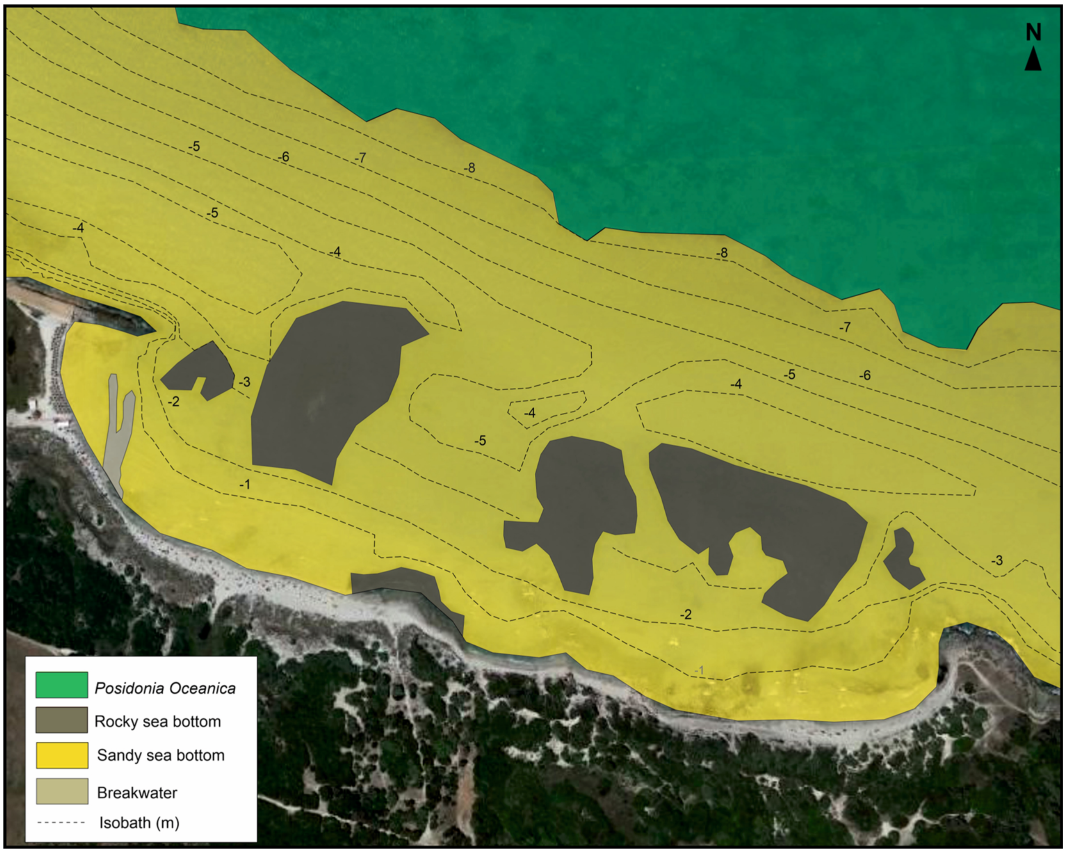

Figure 12. Sea bottom of Torre Guaceto beach. During winter seasons, the rocky sea bottom, located between 2 and 5 m depth causes the wave energy loss and induces dissipation. In summer, the energy dissipation zone moves between the shoreline and the shoals.

obtained by the shoreface and foreshore investigation, whereas improvement of knowledge about longshore material motion can be acquired by analysing the samples along the shoreline. In particular, mean sizes increase from the far ends to the central portion of the beach where a short rocky littoral sector occurs and where the samples collected around it are less sorted (figure 6a and b). As regards skewness and kurtosis, these parameters show slight variations along the shoreline, although the sand samples around the central sector (Bat8 and Bat9) are characterised by tails towards the coarse fraction (figure 6c and d). The results of the textural investigation and Delft3D models suggest that the wave direction from N0° and N330° are responsible for the main storm events during the winter and summer seasons (figure 11). During these events, the sediments eroded from the south-eastern promontory and deriving from the offshore are transported longshore towards the central sector and deposited close to the embayment near the rocky sector (figure 13). Whereas, in the northern sector of the coast, the sediments directly derived from the offshore are accumulated in the central sector of the beach (figure 13). By comparing the model with the DTM investigation between 2018 and 2019, accumulation areas are also highlighted in the central part of the beach and in the embayment close to the rocky sector, whereas the southern parts fall into the stable/erosional range, particularly at the dune base (figure 4).

The compositional data point out a significant variability of the beach sand (figures 9 and 10). The northern and central sectors of the beach are mainly characterised by bioclastic sands associated with *P. oceanica*, which is located between 8 and 25 m depth, whereas hybrid sands are deposited in the southernmost part. These results suggest that the siliciclastic grains, mainly deriving from the erosion of the dunes and headlands and partly from the Ofanto river, are deposited to the southern sector of the beach, which is the most exposed part of the wave motion (figure 13). In addition, due to the slight longshore transport from the south to the north (figure 13), the more porous and lighter bioclastic sediments are removed from the southern sector

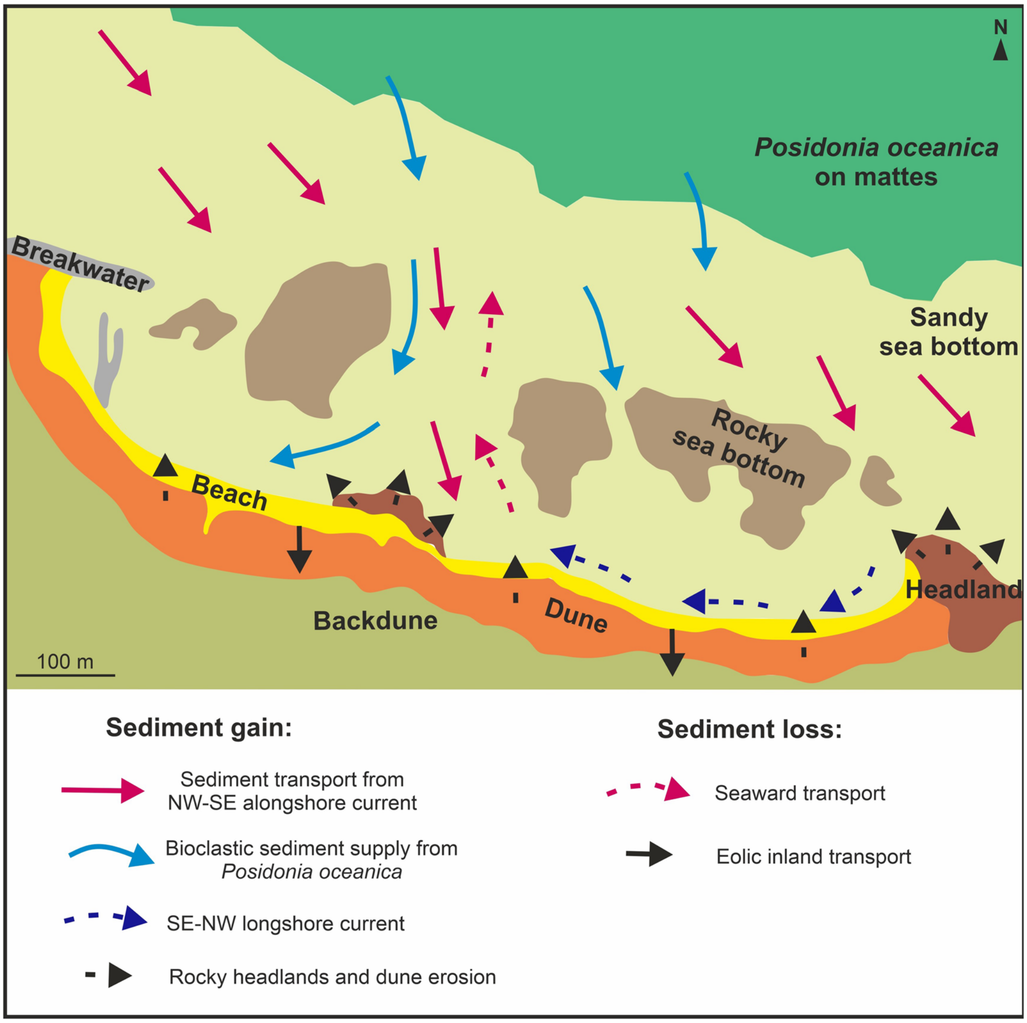

Figure 13. Scheme showing the sediment dispersal in the embayment of Torre Guaceto beach.

and transported to the central part of the beach, indirectly increasing the percentages of the siliciclastic minerals in the southern sector and explaining the longshore compositional sand variability of Torre Guaceto beach.

As regards the shoreface, the general variation of the grain-size parameter with depth (figure 7) highlights a decreasing mean size trend from the swash zone to 6 m depth, particularly along transect A. A lower sorting range is observed between 3 and 5 m depth, particularly during summer seasons and where tail to coarse materials and higher kurtosis values are observed. This result suggests the presence of frequent high-energy events that continuously select the sediments in this sector of the shoreface and where wave breaking occurs as depicted in the Delft3D dissipation model (figure 11). Moreover, the samples collected along transect B are characterised by less-sorted sands with more negative skewness values and leptokurtic curves, suggesting an erosional evolutionary trend than transect A. Similar results were derived from the OTS investigation by comparing the bathymetric profiles between summer and winter seasons (figure 5). Both transects are characterised by erosional trend particularly until 2 m depth which can be attributable to the significant erosive action of winter storms. Nevertheless, the amount of eroded material along transect B is higher than transect A.

5. Conclusions

In this study, the seasonal evolutionary trend of Torre Guaceto beach has been evaluated through a geomorphological and sedimentological point of view. This multidisciplinary approach was considered the most appropriate to describe the processes of erosion, transport, and sedimentation of a pocket beach on a seasonal scale, because the complexity of this closed system, where additional monitoring techniques were needed.

The main findings derived from the investigation highlights that the northern–central sector of the beach falls into the accumulation area, whereas the central–southern sector ranges between stable and erosional trends. These tendencies mainly refer to annual variations which highlight the retreat of the dunes in the southern sector as underlined by the morphology of the profiles extracted from the DTMs. The topographic results are confirmed by the sedimentological and Delft3D model analyses, which explain the grain-size variations in accordance with the sediment transport showing the main differences between the northern and southern sectors of the beach. Finally, the compositional study points out a significant variability of the beach sand. The northern and central sectors are mainly characterised by bioclastic sands associated with *P. oceanica*, whereas hybrid siliciclastic sands are deposited in the southernmost part.

This multidisciplinary research underlines the importance of comparing data from different sectors of the earth sciences that would enrich the amount of missing information about complex and dynamic systems as the beach environment and would increase their interpretative meaning. Gathering various analyses (geomorphological, sedimentological, petrographic and ecological) provides a reliable interpretation of beach dynamics as the results can support each other.

Moreover, the findings obtained in this study could influence the fossil research. Environments at the same depth could have different compositions due to the main sediment selection caused by the wave motion and the current transport system as shown in the compositional variability between northern and southern sectors of Torre Guaceto beach.

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Author statement

All the authors have actively participated in the preparation of the final proof of the manuscript. I Lapietra, M Moretti, S Lisco and F Sabatier conceived the study. Sampling procedures have been carried out by I Lapietra, S Lisco and C Pierri. Sedimentological analyses have been conducted and interpreted by I Lapietra, S Lisco, M Moretti and S Milli. Petrographic and bioclasts evaluation analyses have been carried out by I Lapietra and S Lisco. M Moretti and G Mastronuzzi have realised the geological framing of the area. Topographic data have been collected and interpreted by I Lapietra, G Scardino, G Mastronuzzi and F Sabatier. Delft3D models have been realised and interpreted by I Lapietra and F Sabatier. The integration of sedimentological, petrographic and topographic data has been carried out by I Lapietra, M Moretti and S Lisco. S Milli contributed to the critical revision of the paper.

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