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COASTAL MODELS AND BEACH TYPES IN NE SICILY: HOW DOES COASTAL UPLIFT INFLUENCE BEACH MORPHOLOGY?

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ABSTRACT: S. Longhitano, A. Zanini, *Coastal models and beach types in NE Sicily: how does coastal uplift influence beach morphology?* (IT ISSN 0394-3356, 2005).
This paper compares morphological and sedimentary characters of beach types occurring along the Ionian coastline of NE Sicily and local coastal uplift rates, with the aim of evaluating how vertical coastal movements influence beach morphologies.
The Ionian coastline of NE Sicily may be divided into many coastal provinces and subprovinces, following the relative positions that each segment of littoral occupies within the general geological setting of the central Mediterranean. This coastline runs perpendicularly along the Africa-Europe plate boundary, crossing successions belonging to the chain, volcanic products, a foredeep and a foreland sector.
In this paper only the northern sector, pertaining to the chain and volcanic coastal provinces, is examined. From the south to the northern edge of NE Sicily, four main localities were chosen for examination: (i) Capo Peloro/Messina; (ii) Taormina/Giardini-Naxos; (iii) Riposto/Praiola; (iv) Ognina/Catania.
In these sites, a series of combined observations on the gradient of the nearshore profile, grain size of sediments, local water dynamics, and uplift rates identified classes of distinct beach types and models.
Results indicate that all these coastal profiles developed recently, due to vertical local tectonic movements rather than control by the width of the continental shelf, the morphology of which is strongly influenced by the Malta escarpment fault system.
Differing coastal uplift rates define classes of beach types in which patterns of morphological and sedimentological characters, together with the hydrodynamics of the nearshore zone, are closely related to Recent tectonic vertical movements of the coast.

RIASSUNTO: S. Longhitano, A. Zanini, Modelli costieri e tipi di spiaggia nella Sicilia nord-orientale: come il sollevamento costiero influenza la morfologia della spiaggia? *(IT ISSN 0394-3356, 2005).*
La correlazione tra una serie di dati derivanti da uno studio di carattere morfologico e sedimentologico con i tassi di sollevamento calcolati lungo tutto il litorale ionico della Sicilia nord-orientale ha permesso di identificare il grado di influenza che i movimenti verticali costieri possono avere sullo sviluppo dei differenti modelli di spiaggia.
La costa orientale della Sicilia può essere suddivisa in province e sotto-province costiere, in stretta relazione con le caratteristiche geologiche e geodinamiche che essa stessa presenta. Il litorale percorre perpendicolarmente il margine di giunzione afro-europeo, attraversando, da nord verso sud, un dominio di catena, un dominio vulcanico, uno di avanfossa ed uno di avampaese.
In questo lavoro vengono riportati i risultati che derivano dalle osservazioni condotte soltanto nel settore costiero di catena e vulcanico.
Da nord verso sud sono state considerate quattro principali località tipo: (i) Capo Peloro/Messina, (ii) Taormina/Giardini-Naxos, (iii) Riposto/Praiola e (iv) Ognina/Catania.
In ognuna di queste località, sono state acquisite informazioni circa il gradiente del profilo sotto costa, il diametro medio dei sedimenti di spiaggia, le caratteristiche idrodinamiche locali e i valori relativi ai tassi di sollevamento dell'area costiera locale.
La combinazione di questi parametri ha permesso di individuare distinte classi di differenti modelli di spiaggia.
I risultati suggeriscono inoltre come la morfologia che caratterizza ognuno dei profili di spiaggia considerati è stata direttamente influenzata dall'azione dei movimenti di uplift costieri, piuttosto che dall'ampiezza della piattaforma continentale, che, tettonicamente controllata dal sistema di faglie della Scarpata Maltese, presente nel settore meridionale, si assottiglia progressivamente verso nord fino a scomparire del tutto.
Le differenti classi e modelli di spiaggia individuati per ciascun settore, mostrano pertanto altrettanto differenti sistemi di drenaggio a monte e caratteri morfo-sedimentologici che vengono direttamente controllati dai locali tassi di uplift.

Keywords: NE Sicily; Ionian coastline; coastal provinces; beach types; coastal uplift rate.

Parole chiave: Sicilia nord-orientale; province costiere; modelli di spiaggia; tassi di sollevamento costiero.

1. INTRODUCTION

The Ionian coast of Sicily (Fig. 1) runs along the eastern part of the island, crossing an important geodynamic part of the central Mediterranean. This littoral extends along terrains belonging to the Africa-Europe plate boundary, normal to the subduction direction (LONGHITANO & ZANINI, 2005; 2006).

In this geological setting, three structural coastal domains are identified: *chain, foredeep* and *foreland*. The three domains may be considered as a series of coastal compartments or provinces (*sensu* FINKL, 2004), and include several examples of various beach types, each characterised by peculiar morpho-sedimentary features, in response to the geological setting within each segment of shoreline developed in Recent times.

The Ionian coast of Sicily has been studied in terms of its coastal dynamics and morpho-bathymetric features of the nearshore zone, sedimentary drift and budget, grain-size beach characteristics (AMORE *et al.*, 1979; 1990), and meteomarine conditions (DI GERONIMO, 1990; FERRETTI *et al*., 2003), disregarding the fundamental role of the coastal geological framework in the control of beach development.

Recent publications about coastal systems analyse the evolution of discriminated transects of different examples of shorelines from over the world in relation to Recent tectonic evolution. In detail, quantification of uplift rates, fault control and relative morphological features of coastal environments identify separate geotectonic coastal provinces. Recent anthropogenic influences are also included in the final evaluation of the coastal setting.

This approach has been neglected in recent studies of the eastern coast of Sicily, and this paper is a first preliminary approach on understanding of the coastline and its setting.

This work describes and classifies some of the most representative beach types occurring along the northern segment of the Ionian shoreline, using sedimentological, morphological and hydrodynamic datasets, in order to identify the various coastal provinces in relation to their respective geological settings and local uplift rates.

2. GEOLOGICAL SETTING OF NE SICILY

The north-eastern coast of Sicily has a N-S (±30°) oriented shoreline, extending from *Capo Peloro* (north) and *Catania* (south) (Fig. 1).

It faces the Ionian Sea and represents a microtidal oceanographic framework: here, only wave action and long-shore currents, controlled by the complex Messina Strait dynamics, influence coastal dynamics.

The rivers outflowing on this coast are the main points of sedimentary input. They drain several areas, producing variable amounts of sediment, depending on lithology, gradient and headland altitude (which, in turn, controls the local rate of rainfall) of the respective drainage basins. From N to S, the Zaffaria, D'Agrò, Letojanni, Alcantara and Macchia are the main rivers.

The studied coastline is the northernmost geodynamic domain of the N-S geological transect (Fig. 2). It lies above terrains representing the thin-skinned expression of a chain and the eastern flank of an active volcano, which, in turn, are counterparts of an extremely complex subduction zone running between the African plate (to the S) flexured beneath the European plate (from the N) (Fig. 1, inset).

2.1 Morphotectonics

North-eastern Sicily runs perpendicularly to the southern margin of the Tyrrhenian basin, which includes Calabria (Gvirtzman & Nur, 1999a,b). The study area consists of sedimentary and metamorphic rocks within a south-verging system of nappes of the Appenine–Maghrebian Chain, overthrusting the northward-dipping African plate.

The Malta Escarpment is the most important active tectonic structure influencing the evolution of the NE coast of Sicily. It produces a dip-slip displacement, amounting to 3 km onshore. Where it intersects the coast on the eastern side of Mt Etna, a series of active faults (the Timpe fault system) occur, forming scarps of up to 200 m and fault planes displaying both dip-slip and right-oblique slip kinematic indicators (Lanzafame *et al.*, 1996; Monaco *et al.*, 1997).

The orientation of the entire coastline within this domain is strongly controlled by the structural pattern

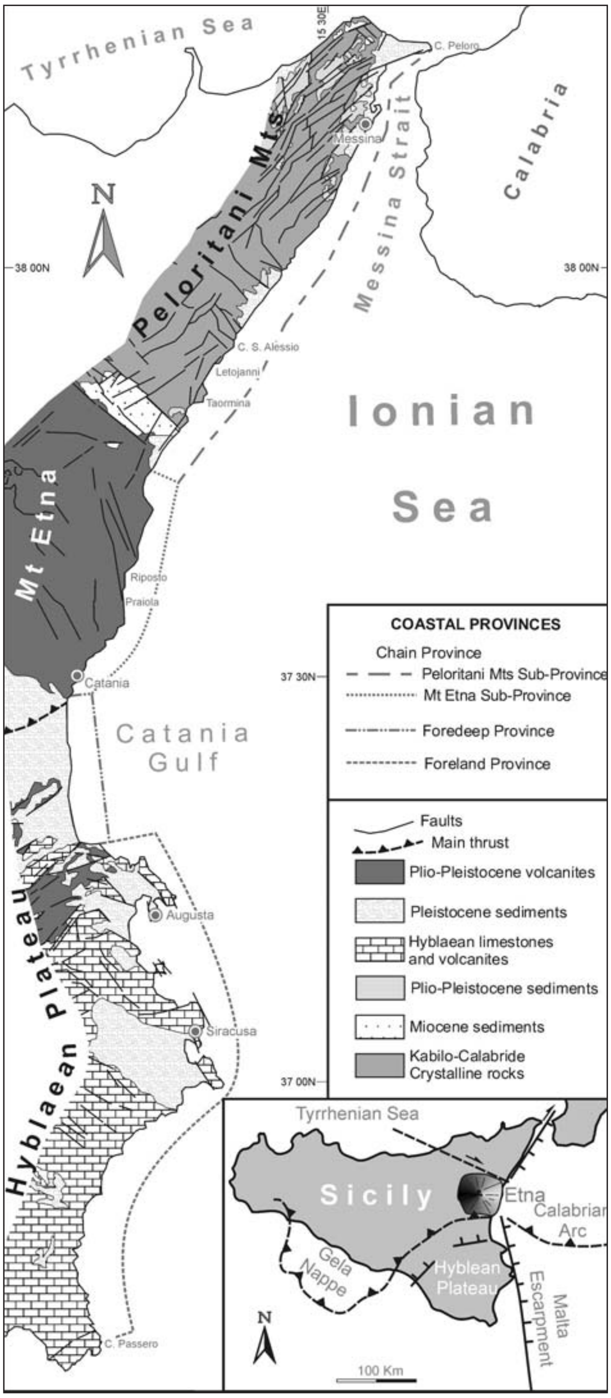

Fig. 1 - Ionian coast of Sicily and geological setting (inset). Many coastal provinces and subprovinces are identified, according to respective geological frameworks. The study sites mentioned in this paper are mainly located along the Chain Province, divided from N to S, into the Peloritani Mts and Mt Etna subprovinces.

Schema geologico generale della costa ionica della Sicilia ed assetto strutturale (riquadro). Il litorale può essere suddiviso in alcune province e sotto-province costiere in relazione al locale assetto geologico. Il tratto costiero studiato per il presente lavoro interessa principalmente la provincia più settentrionale, ulteriormente divisa da N a S in Peloritani Mts subprovince e Mt Etna subprovince.

of the faults dissecting the area. The most important structure intersecting the faults associated with the Malta Escarpment is the seismogenetic NNE-SSW-striking Messina fault system which caused the Messina earthquake (approximate magnitude 7.5) in 1908. This system defines the north-eastern coastline bordering the Straits of Messina and extends south to the Taormina area. On strike, fault scarps also cut the surface of Holocene deposits on the eastern side of Mt Etna, and are connected with the faults of the Timpe system (LANZAFAME *et al*., 1996).

The continental shelf flanking this coastal domain has a high gradient (3-4°) and a narrow seaward extension which progressively thins northwards (from 2.0 to 0.4 km).

This complex structural setting has produced cliffed shorelines and promontories, and pocket, shingle and sandy beaches. Each single type and its morphology also reflect the influence of lithology and uplift rate of the pertaining coastal province.

2.2 Lithologic units

The onshore lithologic units of the study area represent the southern flank of the Calabrian-Peloritani Arc (AMODIO-MORELLI *et al*., 1976), formed of Hercynian crystalline terranes, variously deformed according to a series of ESE-verging thrust-sheet systems, and their Cenozoic sedimentary covers (LENTINI *et al*., 1995; DI STEFANO & LENTINI, 1995; LENTINI *et al.*, 2000). Syn- and post-orogenic sediments are represented by Upper Eocene and younger sequences, each indicating a stage in the polyphasic tectonic evolution of the area (LENTINI *et al*., 2000, and references therein).

In detail, the main lithologic units are represented by the conglomerates and sandstone of the Tortonian S. Pier Niceto Fm, very thin Messinian evaporite, Plio-Pleistocene biocalcarenite and Pleistocene-Holocene coarse-grained fan deltas of the Messina Fm. The corresponding coastline has alternating gravelly/sandy shores and promontories.

To the south, the volcanics of Mt Etna lie above the sedimentary Meso-Cenozoic successions. Its Recent effusive-type activity has been greatly influenced by the development of the neighbouring coast (LONGHITANO & COLELLA, 2007). In the last few centuries, lava flows from the eastern flank of the volcano have created a protrusive rocky shoreline, forming the northern margin of the Gulf of Catania. The volcanic coastal subprovince is characterised here by high cliffs, composed of resistent basalt alternating with scoriaceous lava flow deposits.

All these lithologic units, differently involved in local drainage, are recognisable in the mineralogical composition of the sediments of the corresponding beach types pertaining to each single coastal province. Sediment composition varies from metamorphic, carbonatic and arenaceous clasts on the northern coast, to fully volcanic on the southern coast.

2.3 Uplift rates

In the last few years, emphasis has been placed by the scientific community on evaluation of NE Sicily coastal uplift rates and their relationship with onshore geology (BONFIGLIO & VIOLANTI, 1983; DI GRANDE & NERI, 1988; FIRTH *et al*., 1996; STEWART *et al*., 1997; BORDONI & VALENSISE, 1998; RUST & KERSHAW, 2000; MONACO *et al*., 2000; ANTONIOLI *et al*., 2002, 2003; 2004a,b; KERSHAW & ANTONIOLI, 2004; ANTONIOLI *et al*., 2006).

Research on sea-level indicators (marine notches and ^{14}C dated shells) close to the modern sea level at several locations along the coastline (FIRTH *et al.*, 1996; STEWART *et al*., 1997; RUST & KERSHAW, 2000; KERSHAW, 2000) show that different uplift rates were active during the Pleistocene and the Holocene.

The Messina Strait area shows the highest long-term uplift rates in Italy; BORDONI & VALENSISE (1998) indicate a rate of up to 1.2 mm a^{-1} over the last 125 ka. However, evidences reported by MIYAUCHI *et al*. (1994) suggest that the sites of Capo Peloro and Ganzirri are undergoing long-term uplift rates of 0.8 mm a^{-1}. To the south, MONACO *et al*. (2004) and ANTONIOLI *et al*. (2006) obtain Holocene uplift rates of at least 2.4 and 1.2 mm a^{-1} for the Taormina and Capo Sant'Alessio localities (bordered by the Messina fault system) and the Etna area (bordered by the Malta Escarpment), respectively.

New data from shell remains from the Taormina area north of Mt Etna have been used to show that uplift over the past 6000 years (short-term) had a slower rate of about 1.4 mm a^{-1} (ANTONIOLI *et al.*, 2003; KERSHAW & ANTONIOLI, 2004).

3. METHODS

Our observations were made along the studied coastline according to its geological characters and significance. For each site, shore profiles were measured, starting from mid-swash and moving landwards to the foredune. Beachface sediments were sampled at points where relevant grain-size variations occurred. Sampling density was designed with respect to the total length of profiles, varying from site to site and

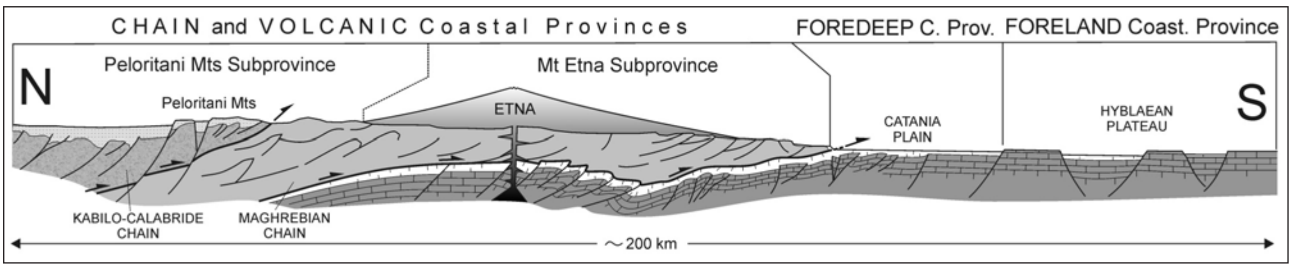

Fig. 2 - Geological cross-section along Ionian coast of Sicily, showing coastal provinces and subprovinces proposed in this study.

Sezione geologica schematica attraverso la costa ionica della Sicilia orientale, mostrante la suddivisione in province e sotto-province costiere proposta in questo lavoro.

depending on the local beach dimensions. Sediment grain-sizes were compared with those of previous works (e.g. AMORE *et al.*, 1992). Statistics covered the means, standard deviations, skewness and kurtosis of grain sizes and settling velocity distributions of sediments.

Environmental parameters associated with the location of each sediment sample were determined from field observations and analysis of aerial photographs. Beach morphology and shoreline stability were identified from bathymetric charts and interpretations deriving from previous works.

For each single location, Dean's Surf Scaling (DSS) parameter was calculated (Dean, 1991), in order to define numerically the rate of energy dissipation or reflection along an idealised nearshore profile. Estimates take into account the characteristics of the dominant wave motion and the physical features of beach sediments, according to the following formula:

$$\Omega = \frac{H_b}{ws\ T} \quad (1)$$

where H_b and T are breaker height and period respectively, obtained from local measurement stations between January 2003 and January 2006, and ws is mean sediment fall velocity. Parameter ws was obtained from the following formula:

$$ws = \frac{2}{9} \frac{a^2 (\sigma - \rho)\ g}{\eta} \quad (2)$$

in which a and σ are particle grain size (radius) and density, respectively; ρ is fluid (marine water) density; g is gravity acceleration, and η is fluid dynamic viscosity. Formula (2) derives from Stoke's law, in which falling velocity is proportional to the square of the particle radius (ALLEN, 1982).

Formula (1) was calculated for nine sites. Results are summarised in Table 1.

4. COASTAL PROVINCES

The northern segment of the Ionian coast of Sicily has a regular N30°-trending shoreline, composed of various beach types. This coastal domain has a total length of 107.36 km and extends from *Capo Peloro* (to the N) to *Catania* (to the S). On the basis of geological

Table 1 - Hydrodynamic setting of nearshore profiles for study areas (from N to S) along NE Sicilian coastline, according to Dean's Surf Scaling Parameter values. Mean breaker heights and periods obtained from *in situ* measurements and 'Catania buoy', mainly from January 2003 to January 2006. See text for explanation on mean sediment fall velocity.

Identità idrodinamica calcolata nei confronti dei profili sotto costa di ciascuna area di studio (da N verso S) lungo la costa nord-orientale della Sicilia, secondo i valori del Dean's Surf Scaling Parameter. L'altezza media dei frangenti ed il periodo sono stati ottenuti da alcune misure in situ *e principalmente dai dati della 'Boa di Catania', nel periodo Gennaio 2003-2006. Fare riferimento al testo per il calcolo del valore ws.*

Site of measurements (from N to S)	Mean breaker height (H_b) m	Mean breaker period (T) sec	Mean sediment fall velocity (ws) cm · sec-2	Dean's Surf Scaling Parameter (Ω)	Beach-type
Capo Peloro/Ganzirri	0.32	6.34	0.39	5.2	intermediate
Messina	0.22	4.00	0.20	4.2	intermediate
Rocca Lumera	0.089	5	0.075	5.9	intermediate/dissipative
Letojanni	0.089	7.10	0.10	6.1	slightly dissipative
Taormina	0.089	3.30	0.36	0.8	slightly reflective
Giardini-Naxos	0.045	6.30	0.16	1.7	intermediate
Riposto/Praiola	0.750	1.50	56,25	0.02	highly reflective
Fondachello	0.750	5.40	40,5	0.1	reflective
Catania/Ognina	0.048	2	32	0.003	very highly reflective

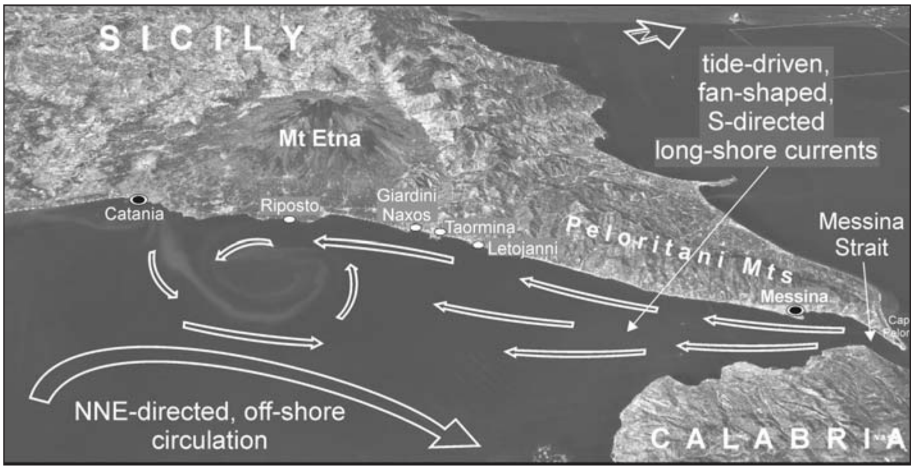

Fig. 3 - Overall seawater circulation of NE Sicily. S-directed, long-shore currents, due to Messina Strait, hydrodynamics interact with clockwise, offshore circulation of Ionian Sea.

Circolazione marina del settore nord-orientale della Sicilia. Le correnti lungo costa, dirette verso meridione e generate dallo Stretto di Messina, interagiscono con le correnti a largo dello Ionio, producendo dei locali movimenti rotazionali in senso orario.

and morphological characters, this province may be further divided into two subprovinces: (i) a northern segment, consisting of the Ionian side of the Peloritani Mts from Capo Peloro to the city of *Riposto* (first 75.1 km), where the Kabilo-Calabride terranes outcrop; (ii) a southern segment, made up of the volcanics of the eastern flank of Mt Etna, down to the city of Catania.

4.1 Coastal hydrodynamics

The Peloritani subprovince, is the coastal segment most strongly influenced by the complex Messina Strait seawater dynamics (DE DOMENICO, 1987). Throughout this narrow waterway, connecting the Tyrrhenian to the N and the Ionian to the S, reverse flows of strong tidal currents occur in phase opposition every six hours, whereas in the microtidal regime of the Mediterranean, tidal currents run at a speed of 6 or 7 knots on the surface (MONTENAT *et al*., 1987). These hydrodynamics control seawater movement along the Peloritani coastal subprovince, where a fan of S-directed currents develops (Fig. 3). These flows give rise to SSW-directed long-shore currents, controlling the coastal drift of sediments.

The seawater dynamics of the Messina Strait also influence water circulation along the southern coastal subprovince, where generally S-directed long-shore currents flow. Here, they interact with the volcanic promontory of the eastern flank of Mt Etna and with NNE-directed offshore circulation, producing a series of clock- and anticlock-wise cells (LONGHITANO & ZANINI, 2002), marked by the turbidity plumes of suspended loads debouching from the main rivers, visible in satellite photographs (Fig. 3).

4.2 Beach types

The absence of a wide continental shelf which is characteristic of the NE coast of Sicily has deeply influenced the morphology of the relative beach types. Narrow beaches are generally found, extending for several kilometres. Other types consist of strips of coarse-grained material, constrained between promontories. The average gradient is medium-high (up to 9°) and the isobaths of the nearshore zones describe a narrow, rapidly subsiding sea-floor: the bottom deepens regularly to -1000 or -1500 m, without any shelf break (ramp-type shelf).

The beach types which are more representative of this coastal domain are described in four main sectors, located from N to S: (i) Messina and (ii) Taormina, within the Peloritani Mts coastal subprovince, and (iii) Riposto and (iv) Ognina (Catania), within the Mt Etna subprovince.

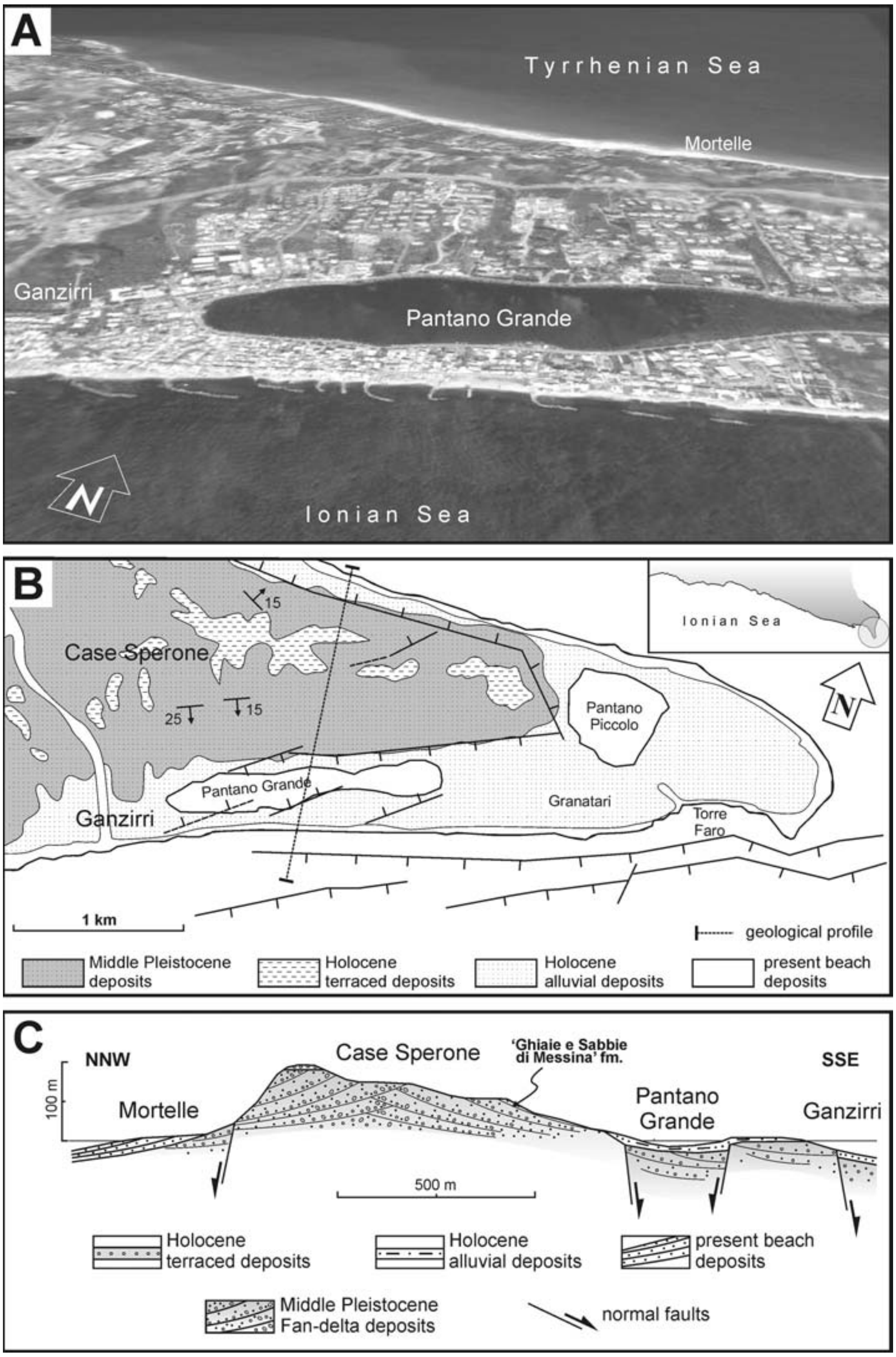

Fig. 4 - (A) View of Capo Peloro and Ganzirri coastline; (B) geological map; (C) profile (modified after BOTTARI *et al.*, 2005).

(A) Vista panoramica di Capo Peloro e della costa di Ganzirri. (B) Schema geologico del settore e relativa sezione (C) (modificata, da BOTTARI et al.*, 2005).*

4.3 Peloritani Mts Subprovince

4.3.1 Messina area

The Messina and Capo Peloro types are represented by sandy beaches, NE-evolving to a sandy-gravelly spit, which grew during the late Holocene transgression due to the action of littoral current circulation (SEGRE *et al.*, 2004).

The beaches in the Messina area are mainly formed of shingle and sandy types, with morphological configurations directly influenced by the high hydrodynamics of the Messina Strait.

The Capo Peloro spit-peninsula (Fig. 4A) extends from Ganzirri to Granatari-Torre Faro, and consists of a highstand lagoon and eolian coastal deposits overlying transgressive marine sand. The latter deposits represent Middle Pleistocene coastal wedges, prograding during a relative sea-level rise toward the Messina Strait and eroding Lower Pleistocene regressive fan-delta deposits (MESSINA Fm., *Auct*.; Fig. 4B).

The beach type that summarizes this geological framework shows a wide coastal plain, with a gentle landward inclination. This morphological setting derives from the accommodation space generated by roll-over of the normal-fault hanging-wall, where Holocene salt-marsh sedimentation takes place (Fig. 4C; BOTTARI *et al*., 2005).

The nearshore beach profile may be considered as the remnant of a beach-barrier system which, strictly controlled by the anthropogenic activity of the last few centuries, has lost its original morphology (Fig. 5).

The DSS parameter calculated for the nearshore profile ranges from 4.1 to 5.2, indicating an intermediate stage between dissipative and reflective domains. This is also shown by the seaward increase in the beach gradient: the nearshore profile evolves from slightly dissipative to reflective type, although dominant wave energy is mitigated by the action of the Messina Strait tidal currents flowing parallel to the shore (Fig. 6).

4.3.2 Taormina area

The Taormina area comprises a number of promontories and islands (Fig. 7), amounting to several kilometres of limestone-bordered coastline. This uplifted headland area is located on the relatively downthrown side of a major fault, whose strike corresponds to that of the Messina system and which generally bounds the coastline in this area (RUST & KERSHAW, 2000).

The shore is represented by cliffs with debris accumulations at the base, without abrasion platforms.

When present, the beach is compartmentalized into shingle pocket clast accumulations occurring

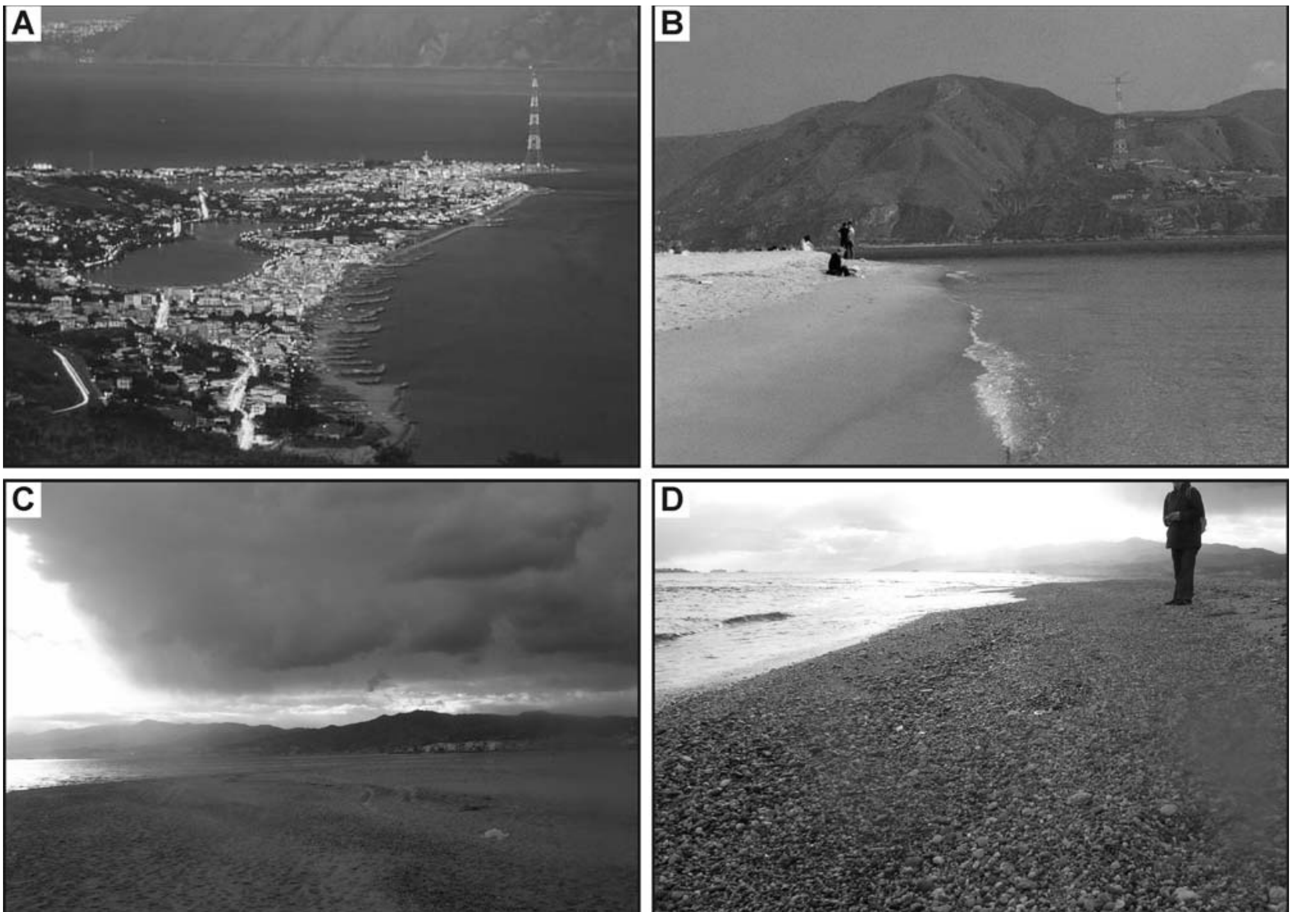

Fig. 5 - (A) View from south of Capo Peloro and Ganzirri area; (B, C, D): details of beach types occurring along coast.

A) Vista meridionale dei settori di Capo Peloro e Ganzirri. (B, C e D) Particolari dei modelli di spiaggia osservabili lungo questo litorale.

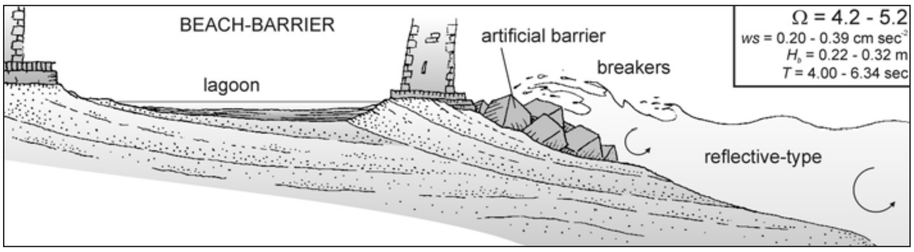

Fig. 6 - Beach type and nearshore profile of Capo Peloro/Messina area. Original morphology of previous beach-barrier system profoundly modified by anthropogenic activity along coast in last few centuries. (Ω = Dean's Surf Scaling parameter; *ws* = mean sediment fall velocity; H_b = mean breaker height; *T* = mean breaker period).

Modello di spiaggia schematico e profilo sotto costa relative al settore di Capo Peloro/Messina. Si noti come l'originale assetto morfologico di un sistema di tipo barra è stato profondamente modificato dall'azione antropica lungo costa degli ultimi secoli.

within indentations (Spisone, Isola Bella) and by sandy prograding beaches on the embayments (Giardini-Naxos, Figs. 7A, 7B).

The S-directed long-shore seawater circulation is diffracted by the irregular coastline and a series of local clock- and anti-clock-wise cells develop at local scale.

Beach sediments are composed of metamorphic and calcareous clasts, up to 30 mm in size, organized into a 5°-7° seaward-inclined narrow strip.
Along the shingle beach, relicts of ancient beachrock deposits formed of gently seaward-inclined conglomeratic beds occur, referable to a Recent uplifted beach face (Fig. 8).
The beach for this sector can be described as a reflective-type profile, characterized by a staircase-type section (submerged data are from Antonioli *et al.*, 2003), with a DSS rating of 0.8 (Fig. 9).

A sector which well represents the degree of morphological variability typical of this coastal subprovince is the area of Giardini-Naxos. Located a few kilometers south of Taormina, two promontories, the calcareous Capo Taormina (north) and the volcanic Capo Schisò (south) form a wide gulf (see Fig. 6A). This particular morphology causes local seawater circulation which has given rise to a broad sandy shoal, during the last 5-6000 years (Randazzo, 2003). This morphological setting locally changes the hydrodynamic framework of this part of the subprovince, from a reflective to a local dissipative (DSS = 1.7) nearshore profile (Fig. 8D).

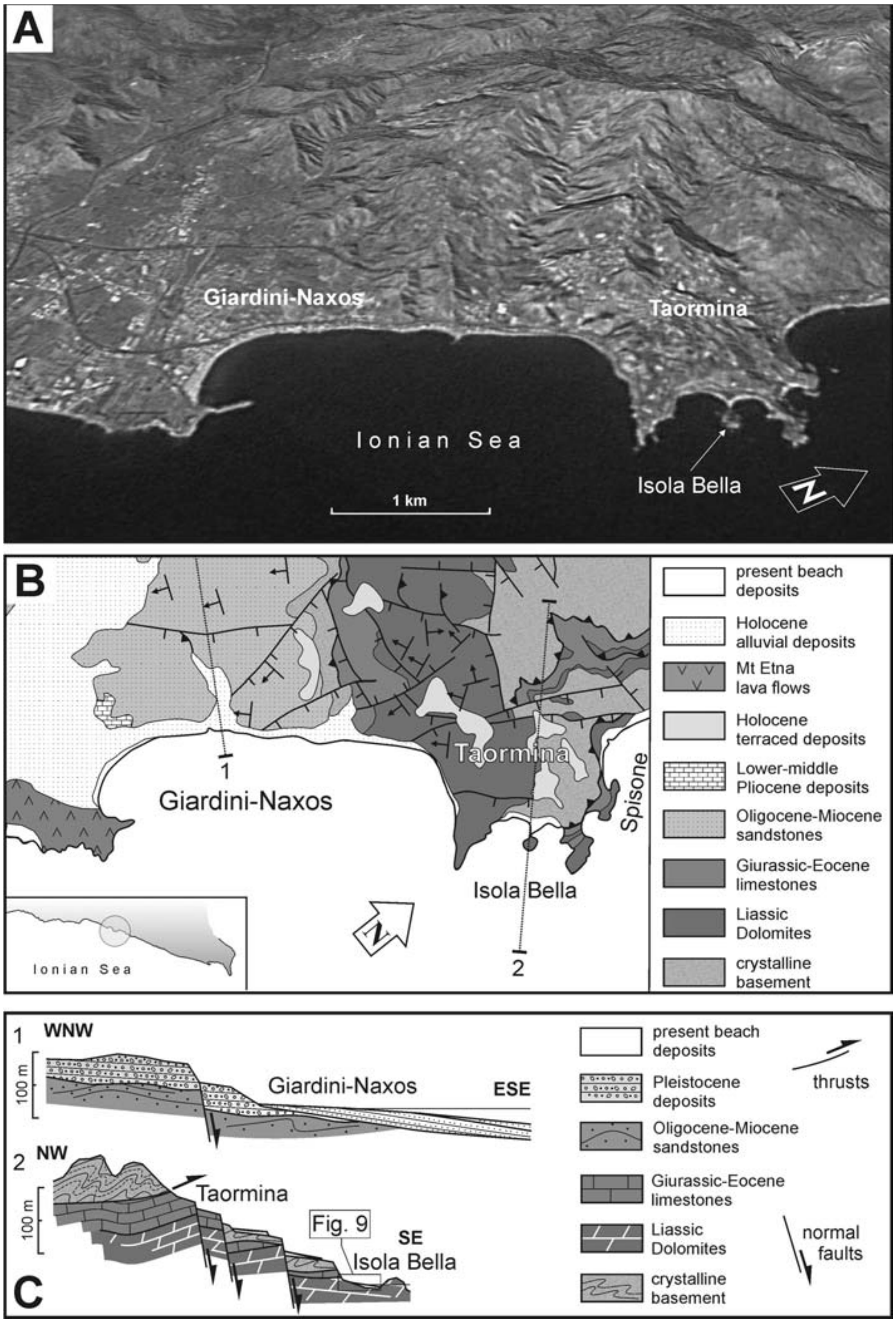

Fig. 7 - (A) View of Taormina and Giardini Naxos coastline; (B) geological map; (C) profile (modified after Lentini *et al.*, 2000).

(A) Vista panoramica delle aree di Taormina e Giardini Naxos. (B) Schema e relativo profilo geologico (C) (modificato, da Lentini et al.*, 2000).*

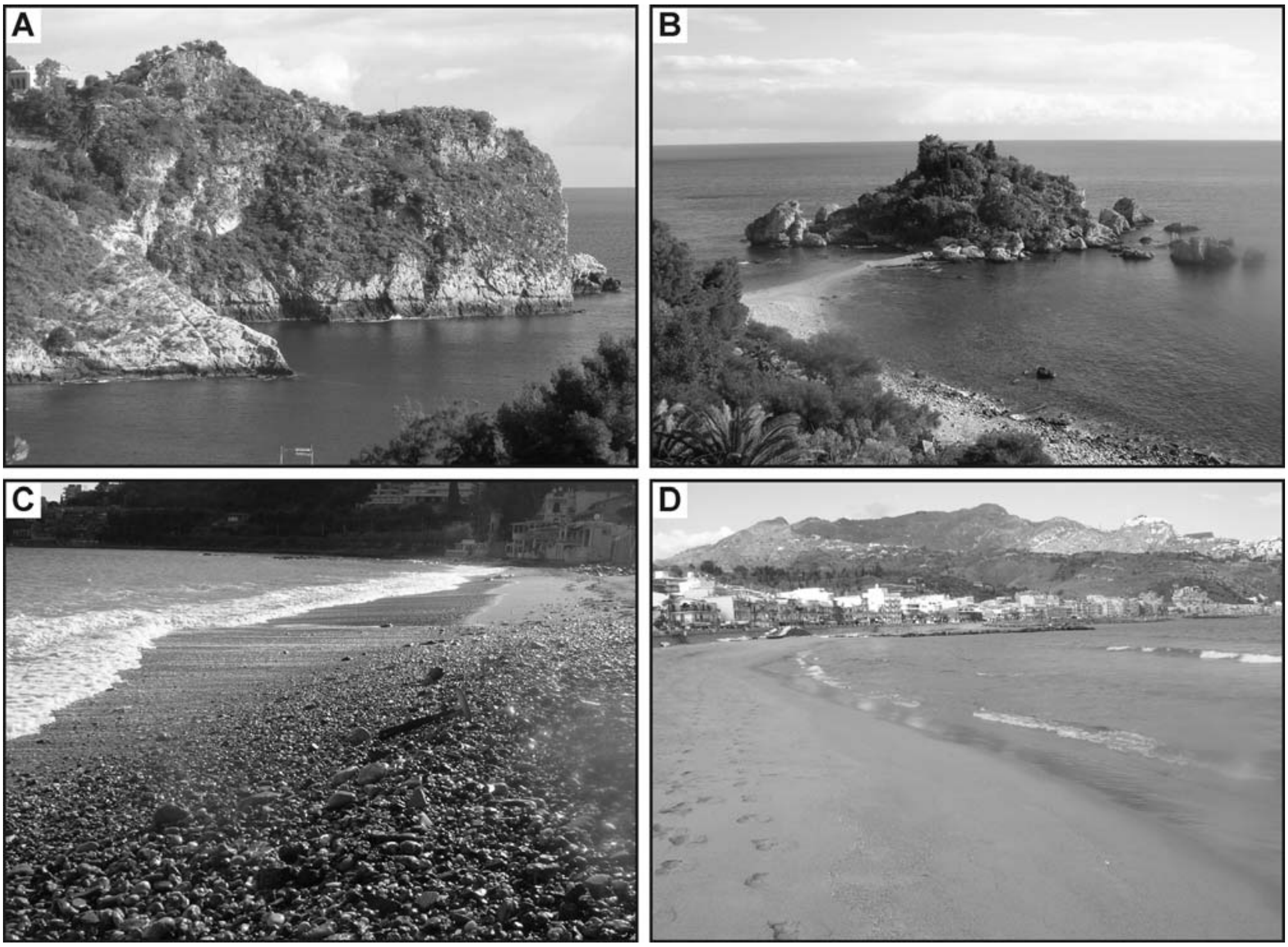

Fig. 8 - (A) Panoramic view of Taormina cliff, showing marine notch 5 m above present sea level; (B) Isola Bella promontory, connected at the coast to a gravel spit; (C) detail of shingle beach type, a few km N of previous photos; (D) beach type at Giardini Naxos.

(A) Veduta panoramica della falesia di Taormina, mostrante un chiaro solco d'erosione marina posto ad un'altezza di circa 5 metri sull'attuale livello del mare. (B) Il promontorio dell'Isola Bella, collegato alla linea di costa attraverso un sottile tombolo ghiaioso. (C) Dettaglio della spiaggia ghiaiosa di Spisone, pochi km a nord delle precedenti foto. (D) Spiaggia sabbiosa di Giardini Naxos.

4.4 MT ETNA SUBPROVINCE

4.4.1 Local coastal hydrodynamics

The eastern flank of Mt Etna has a typical morphology that reflects the progressive emplacement of historic and recent lava flows, due to effusive volcanic activity, reaching the sea and creating a peculiar coastal setting (MONACO *et al.,* 1997).

Here, currents driven by the Messina Strait also influence local seawater circulation, producing longshore S-directed and local N-directed currents. Nearshore circulation is often diffracted and inhibited by the great complexity of the cliffed volcanic shoreline, marked by a number of small coastal promontories and indentations, created by eroding lava deltas.

In this subprovince, only wave energy may be considered as a dominant factor affecting the shoreline and controlling beach sediment re-working. Waves approach the coast obliquely, as a result of the S-directed currents.

4.5 Riposto area

The main tectonic and morphologic feature of

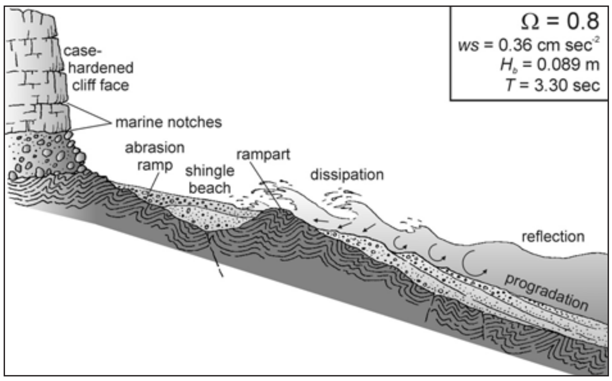

Fig. 9 - Beach type characterizing coastline of Taormina area. A shingle, narrow beach is confined to inner part of a steep, dissipative-to-reflective nearshore profile. (Ω = Dean's Surf Scaling parameter; *ws* = mean sediment fall velocity; H_b = mean breaker height; T = mean breaker period).

Modello di spiaggia relativo alla costa taorminese. L'unica spiaggia ghiaiosa di piccole dimensioni che può svilupparsi appare chiaramente confinata nel settore più interno di un profilo di tipo dissipativo/riflessivo.

eastern Mt Etna is the widespread NNW- and NNE-trending active fault system. The NNW-SSE-oriented Timpe fault system is considered to be the inland extension of the Malta Escarpment (Cristofolini *et al.*, 1979; Lentini, 1982).

Here, a coarse-grained fan-delta deposit occurs extensively (Figs. 10A, 10B). The so-called 'Chiancone' (Kieffer, 1969; 1970; Romano & Sturiale, 1981; Di Grande & Di Maggio, 1988) represents the largest Etnean volcanoclastic sequence (Del Negro & Napoli, 2002).

Some authors (e.g., Calvari & Groppelli 1996; Bousquet *et al.*, 1998) have pointed out that this fan-shaped deposit has a submerged counterpart toward the Ionian, which modifies the isobathic trend of this coastal sector (Fig. 10C).

The beach type is characterized by monogenic volcanic clasts, with the largest grain size observed along the whole Ionian coast of Sicily (Fig. 11).

During high-energy stages, waves rework the clasts along the swash zone, producing very impressive noise and vibration, perceptible quite far from the beach.

Beach morphology here is directly influenced by the size of the clasts, organized into three orders of berms and characterized by a seaward gradient of up to 10° (Fig. 12). The DSS parameter indicates a fully reflective nearshore profile, controlled by oblique wave incidence.

According to Monaco et al. (1997), the beach of this sector developed on the foot-wall of a normal fault. Instead, our observations indicate that it represents sediments which accumulated during the end of the last sea-level rise, occupying the erosional platform caused by the sea during the present sea-level highstand.

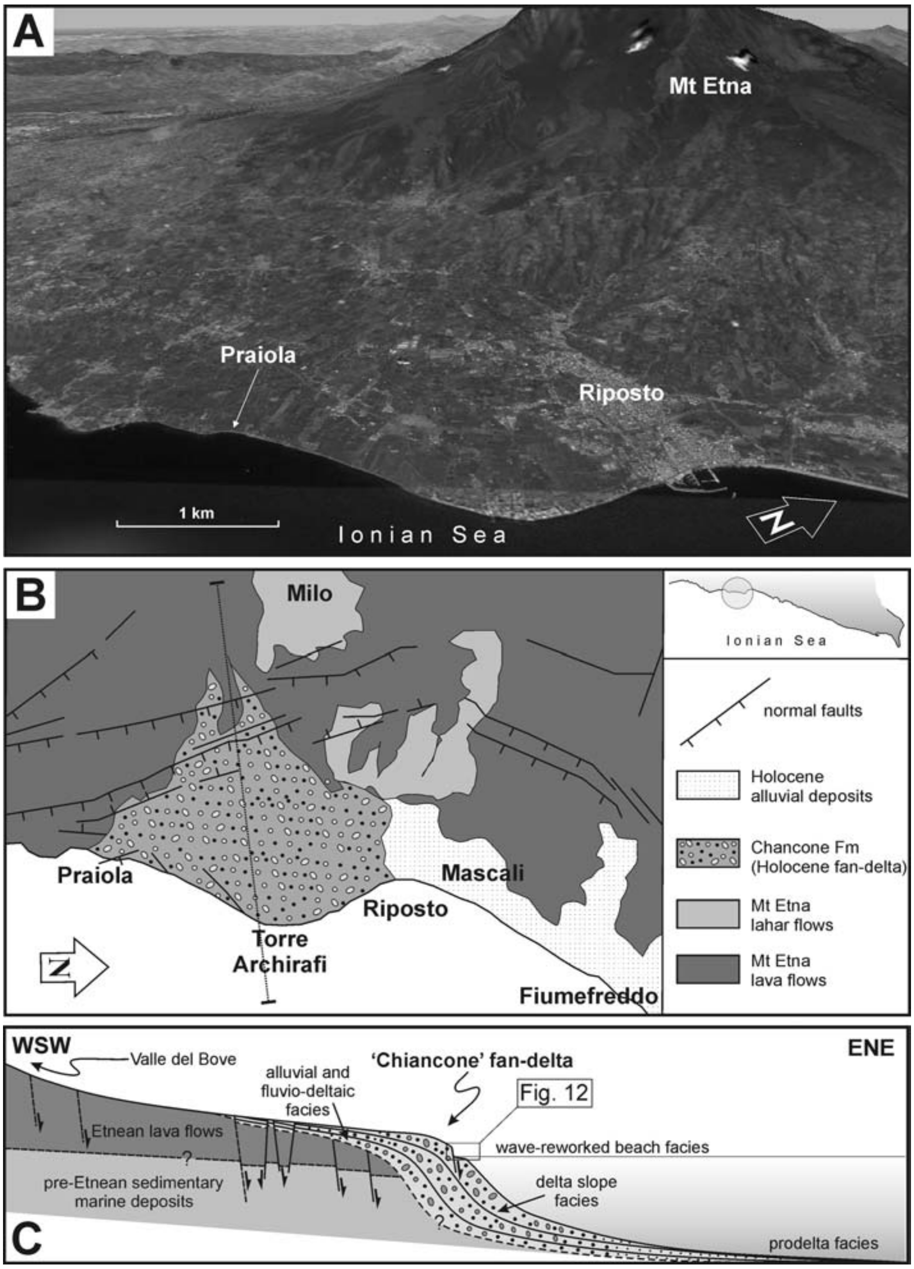

Fig. 10 - (A) View of the Riposto and Praiola coastline; (B) geological map; (C) profile (modified after Del Negro and Napoli, 2002).

(A) Vista panoramica del settore costiero di Riposto e Praiola. (B) Schema e profilo geologico del settore (C) (modificato, da Del Negro e Napoli, 2002).

4.6 Ognina

The youngest normal faults of the Mt Etna area are located along the base of the eastern flank of the volcano. NNW- and NNE-trending fault segments control the present coastal morphology, producing steep Late Pleistocene-Holocene sea cliffs (Monaco *et al*., 1997). The most impressive scarps extend for about 20 km from Acireale to S. Alfio, producing walls up to 120 m high (Fig. 13A).

The terrains forming this cliffed coast are made up of lava flows from eruptions of different ages (Romano & Sturiale, 1982) (Fig. 13B). The coastal morphology is characterized by sea terraces, occupied by Holocene alluvial volcanoclastic deposits (Fig. 13C).

The beach types considered most representative of the southern sector of this subprovince were studied N of Catania, along the shoreline of Ognina. Here, anthropogenic activity is recent and less invasive, and the morphological characters of this coast are still well-preserved (Fig. 14).

The beach type is represented here by small pocket beaches, containing coarse-grained volcanic sediments, deriving only from rock-fall debris of the cliffs, attacked and eroded by the powerful action of

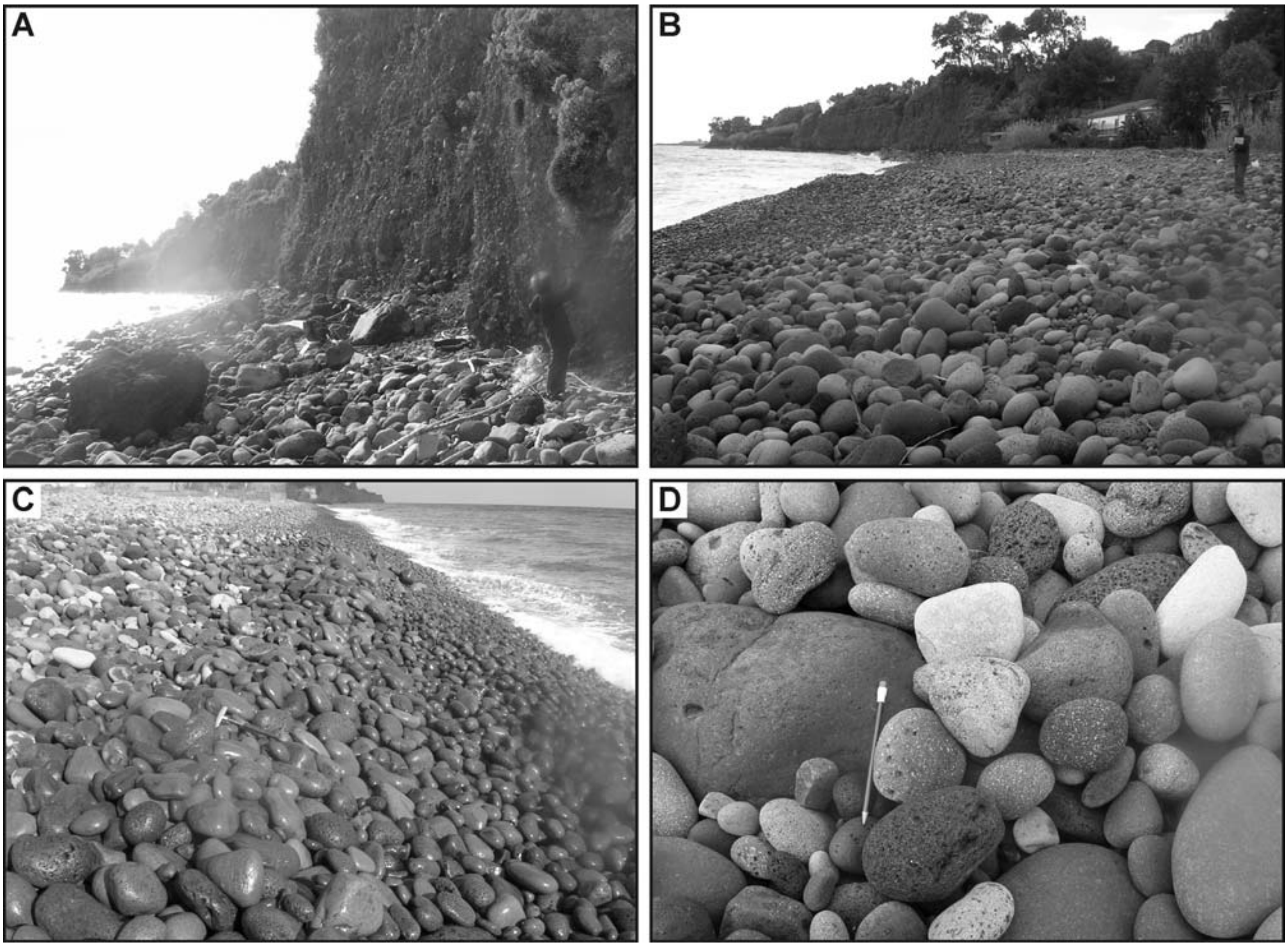

Fig. 11 - (A) Cliff along Praiola beach; (B) detail of same beach characterized by a series of storm berms; (C) volcanic cobbles and pebbles along swash zone; (D) detail of clast morphology.

A) Falesia vulcanoclastica lungo la spiaggia di Praiola. (B) Dettaglio della stessa spiaggia, caratterizzata da una serie di berme generate da episodi di tempesta. (C) Clasti vulcanici lungo la zona di battigia. (D) Dettaglio morfometrico dei clasti vulcanici.

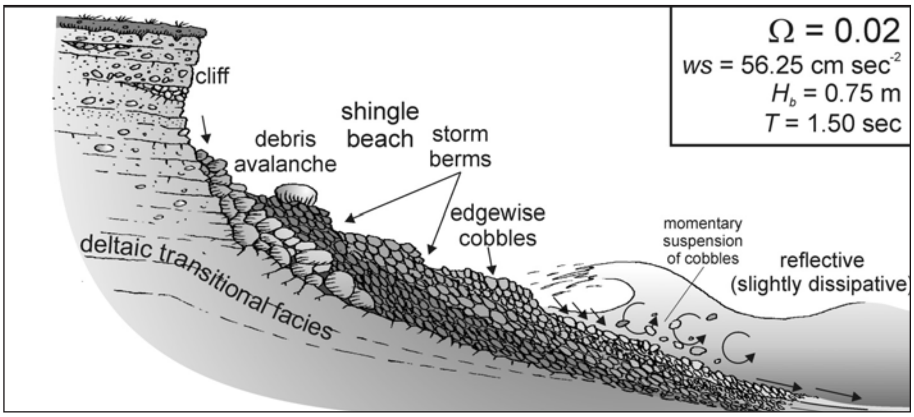

Fig. 12 - Beach type of Riposto/Praiola site. Nearshore profile is reflective, slightly dissipative. Beach develops near a cliff cut due to present sea-level highstand. (Ω = Dean's Surf Scaling parameter; *ws* = mean sediment fall velocity; H_b = mean breaker height; T = mean breaker period).

Modello relativo alla spiaggia di Riposto/Praiola. Il profilo sotto costa è di tipo riflessivo, leggermente dissipativo. La spiaggia si sviluppa occupando il solco erosivo formatosi durante l'attuale stazionamento alto del livello del mare.

waves.

The nearshore profile reflects the morphology of a submerged lava delta front, characterized by a staircase-type sea-bottom which creates a very high reflective-type hydrodynamic setting (DSS parameter 0.003) (Fig. 15).

5. DISCUSSION AND CONCLUSIONS

The subdivision of discrete segments of shoreline, based on the geological framework in which they developed in Recent times, identifies the characters of the beach types in a more analytical way. The morphology

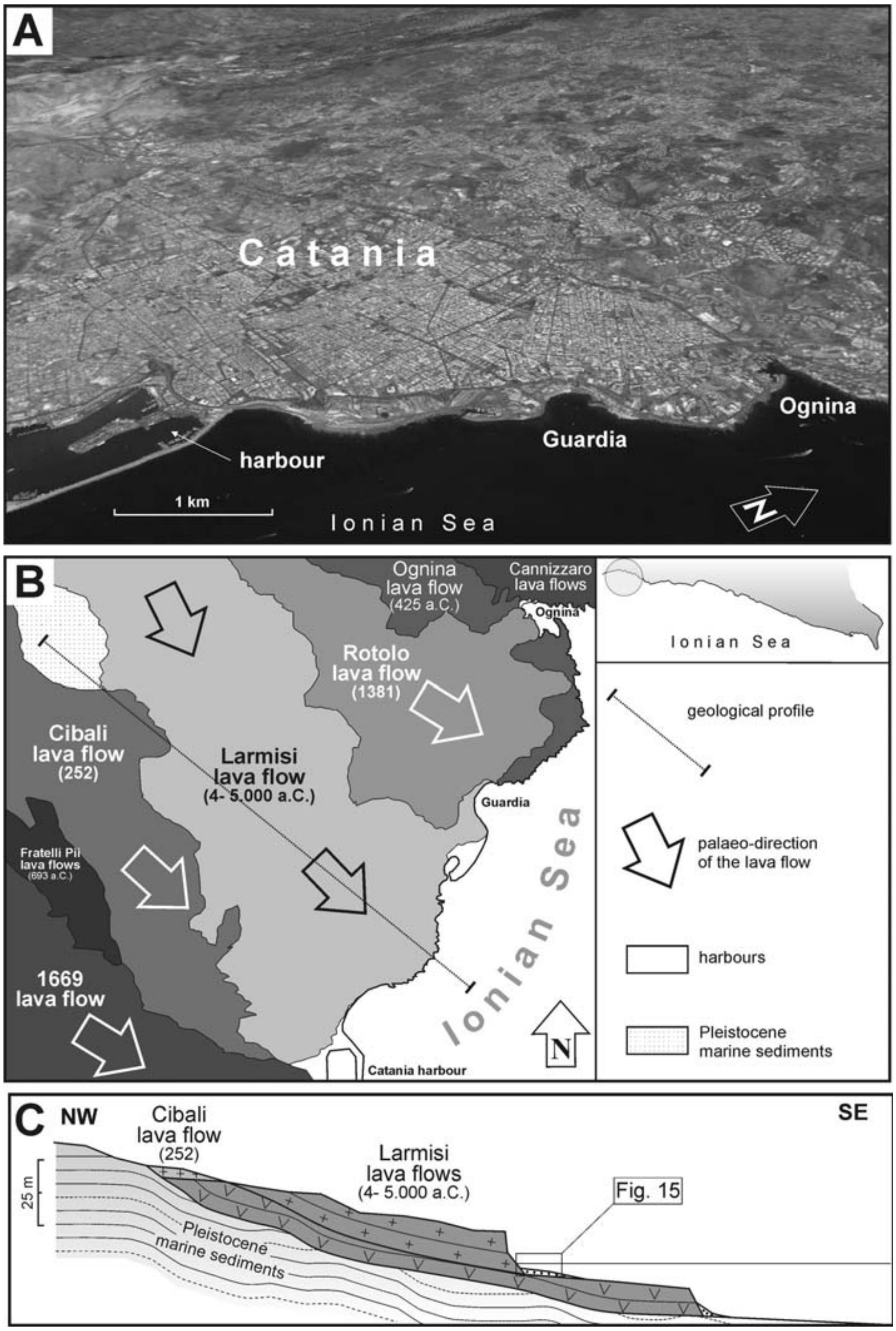

Fig. 13 - (A) View of Ognina and Catania volcanic coastline; (B) geological map; (C) profile (modified after Monaco *et al*., 2000).

(A) Vista panoramica relativa al settore costiero di Ognina e Catania. (B) Schema e profilo geologico del settore (C) (modificato, da Monaco et al.*, 2000).*

and sedimentology of each single coastal segment directly refer to a series of geological considerations, giving a complete framework of the coastal system.

Morphological and sedimentological observations collected from the sites of Capo Peloro-Messina, Taormina-Giardini Naxos, Riposto and Ognina-Catania, in the northern coastal province of the Ionian coast of Sicily, describe a series of beach types which directly reflect the local geological framework.

The present-day aspect of these beaches indicates by long- medium- and short-term processes, the duration of which depended on the time over which they developed within the system.

The general morphology of a coastal compartment influences beach characters in terms of longitudinal/lateral extension of sediments, prograding rate, and wave influence on long-shore sediment distribution. All these elements are long-term features, directly influencing the local geology. In contrast, a series of several different features may be appreciated in beaches, where short-term control processes are active. For example, beach gradient and the physical organization of sediments along the beachface are parameters which depend on grain size and Recent hydrodynamics which, in turn, derive from local meteo-marine conditions. An exception to these considerations is the coastal uplift rate, especially when Recent vertical movements are very rapid. The examples observed in the NE coastal province of the Ionian Sicilian shoreline show several coastal compartments characterized by high uplift rates.

The time-span over which vertical coastal movements have been calculated (125÷5 ka) and their influence on coastal morphology are considered as medium-term controlling factors for the development of a coastal sector. The beach types developing along uplifting coasts are regarded as the variables of a coastal system which best record this condition.

The hydrodynamic identity of each study site, quantified by Dean's Surf Scaling (DSS) parameter, characterizes the dynamic behavior of every beach and its relative nearshore zones. The results are transitional between dissipative, slightly dissipative, and reflective nearshore profiles, depending not only on the parameters included in the calculation (sediment grain size, mean breaker height and length, etc.) but also on the coastal gradient of the bedrock on which the beach developed during Recent times. The gradient of the bedrock is strongly controlled by vertical tectonic coastal movements, which are expressed in coastal uplift rates.

Assuming this background, every beach profile,

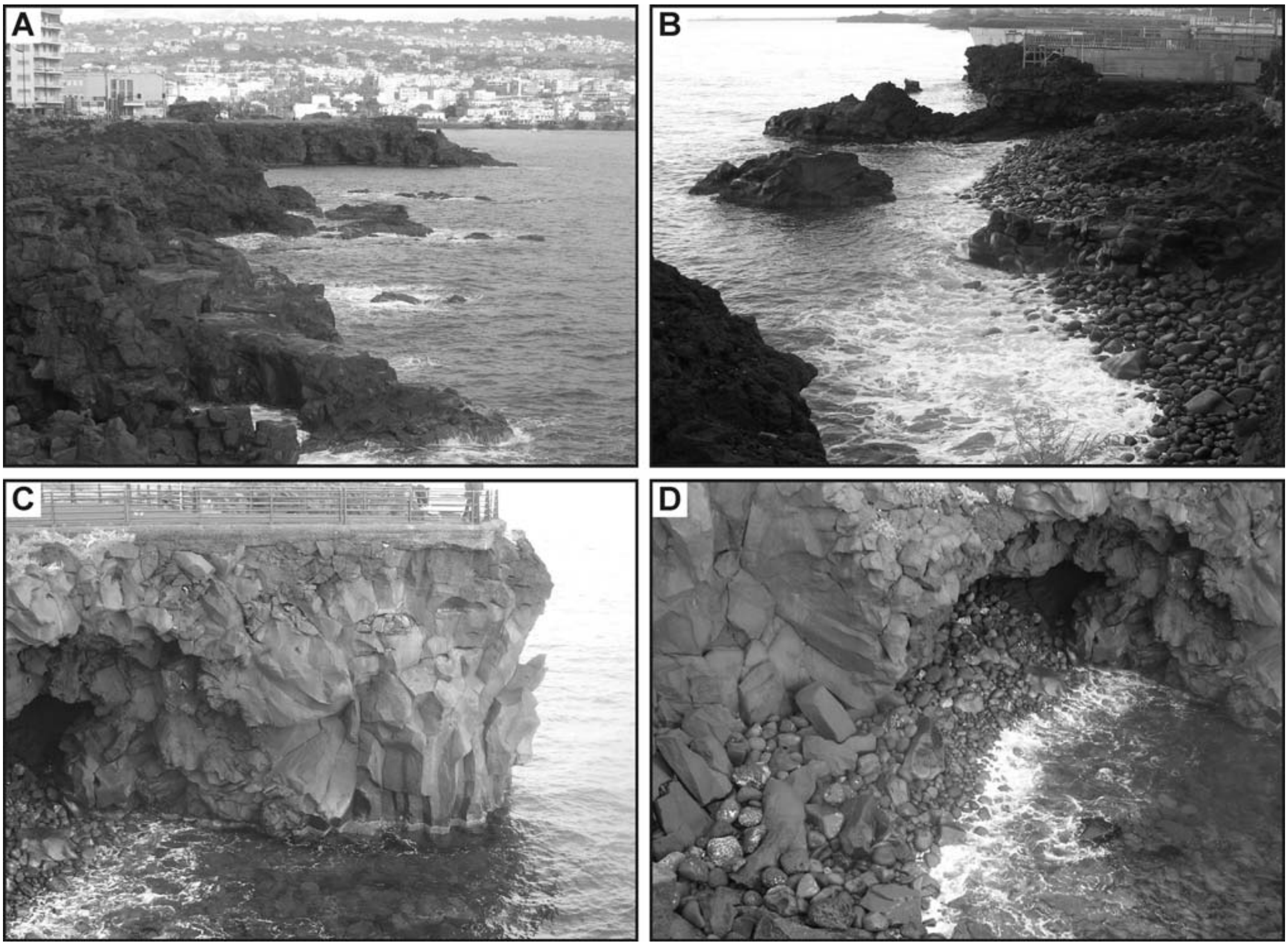

Fig. 14 - (A) Panoramic view of Ognina coastline (from south), typically characterized by lava deltas of historic Etnean eruptions; (B) view of same coast (from north) where pocket beaches composed of volcanoclastic detritus occur; (C) detail of columnar, basaltic cliff; (D) pocket beach at toe of cliff in previous photo.

(A) Veduta panoramica meridionale del settore costiero di Ognina, caratterizzata da spandimenti lavici appartenenti alle eruzioni storiche dell'Etna. (B) Veduta settentrionale del medesimo tratto costiero, dove si sviluppano alcune isolate pocket beach costituite da clasti esclusivamente di natura basaltica. (C) Dettaglio dei basalti colonnari che costituiscono una parte della falesia vulcanica. (D). Dettaglio di una pocket beach presente alla base della falesia ritratta nella foto precedente.

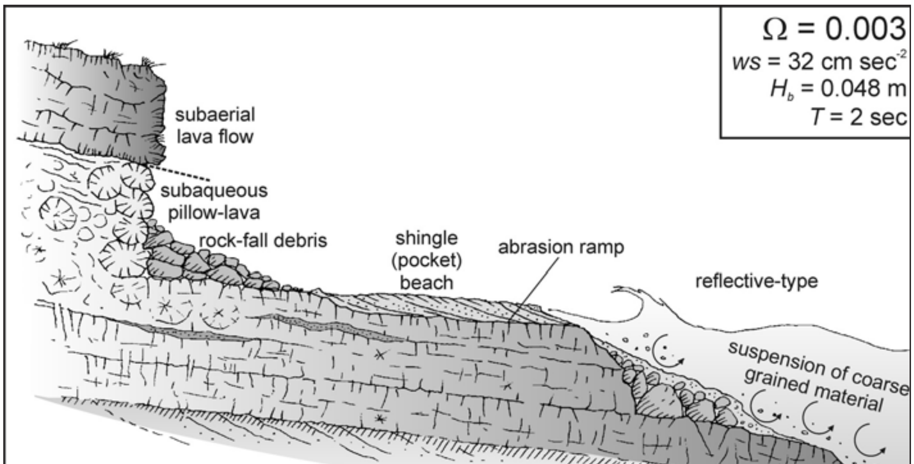

Fig. 15 - Beach type of Ognina/Catania site. Beach occurs at toe of a basaltic cliff, created by erosive action of waves. Beach sediment derives only from debris produced by wave erosion. Reflective type of nearshore profile implies high-energy hydrodynamics and temporal suspension of coarse clasts during storms. (Ω = Dean's Surf Scaling parameter; ws = mean sediment fall velocity; H_b = mean breaker height; T = mean breaker period).

Modello di spiaggia relativo al settore di Ognina/Catania. I clasti basaltici si attestano alla base della falesia lavica prodotta dall'azione meccanica dell'erosione del moto ondoso. Il sedimento deriva esclusivamente dal crollo di porzioni della parete vulcanica. Il comportamento idrodinamico di tipo riflessivo del profilo sotto costa determina la temporanea sospensione di clasti anche di grandi dimensioni durante le fasi di alta energia.

with its morphological, sedimentological and hydrodynamic features, may be referred to the local coastal uplift rate.

Fig. 16 displays the gradient and grain-size of nearshore profiles on the y-axis, and the relative distance along the Ionian coast of Sicily on the x-axis. The first parameter (range: 1÷5) indicates the gradient of the nearshore profile and the sediment grain-size for each single site of observation. As these two characteristics vary in the same way, as gradient and sediment grain-size increase, index values vary progressively from 1 to 5. The uplift rates on the right-hand y-axis define discriminated classes of uplfiting coasts. All these combined parameters show a normal correlation with a gradual transition between dissipative and reflective beach types.

The continental shelf progressively spreads eastward from northern to southern coastal subprovinces (Fig. 16) and shows two main groups of beach types.

The first group corresponds to the models of the northern sector, where the continental shelf progressively thins northwards and the beach types show wide, dissipative-type, sandy inshore profiles, characterized landwards by well-developed alluvial plains. The beach gradients observed at Capo Peloro, Messina and Letojanni are medium-low, and uplift rates of up to 0.8 mm a^{-1}.

The second group contains Taormina, Riposto and Ognina, where the continental shelf widens southwards, and the beach types are narrow, coarse-grained and cliffed with a medium-high gradient and uplift rates of up to 2.4 mm a^{-1}.

Thus, the Ionian coastal province of NE Sicily shows beach types with morphology mainly influenced by local uplift rates, rather than by continental shelf width.

Another way of describing the beach types occurring in the studied subprovinces is shown in Fig. 17. This block-diagram has a series of differing coastal profiles and models, taking each beach type into account: (i) bedrock lithology; (ii) the nature of the feeder system of a given shoreline; (iii) local uplift rates.

In the model of Fig. 17, where beach types are displayed in no geographic order, as uplift rates increase (ranging from 0.7 to 2.4 mm a^{-1}), the feeder systems evolve from wide, well-developed, alluvial braided plains (Letojanni), to torrential-type coarse-grained

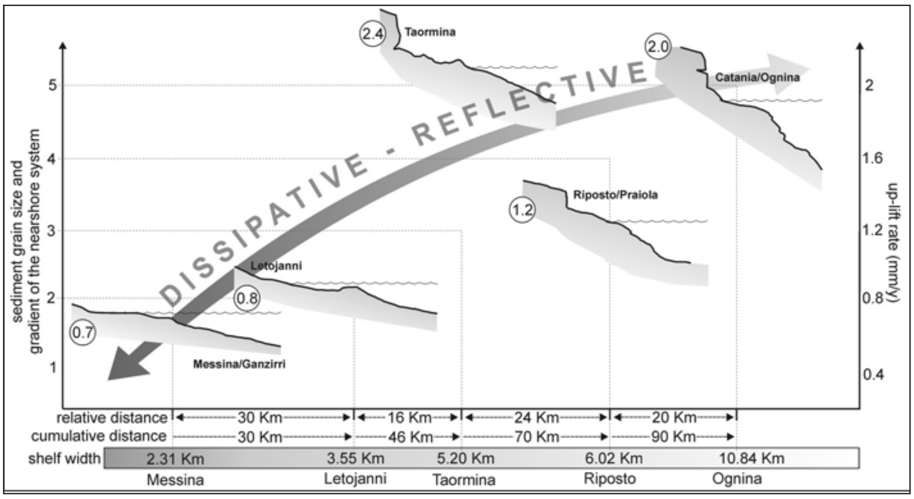

Fig. 16 - Correlation between sediment grain-size and gradient of each nearshore system (studied here) (left-hand y-axis), with local coastal uplift rates (right-hand y-axis), with relative distances of study sites (lower x-axis). Note progressive changes in hydrodynamic behavior of each profile from 'dissipative' to 'reflective' as uplift rate increases. Progressive, southward enlargement of continental shelf does not correlate with gradient of inshore profile.

Diagramma mostrante la correlazione tra diametro dei sedimenti e gradiente di ciascun sistema di spiaggia considerato nel presente studio (asse di sinistra delle ordinate) con i locali tassi di sollevamento (asse di destra delle ordinate), riferiti alle rispettive distanze (relative e cumulative) che separano le diverse aree studiate (asse delle ascisse). Si noti una progressiva variazione nel comportamento idrodinamico di ciascun singolo profilo da 'dissipativo' a 'riflessivo' all'aumentare della velocità del tasso di sollevamento locale. La progressiva espansione verso meridione della piattaforma continentale sembra non correlarsi direttamente con questa caratteristica.

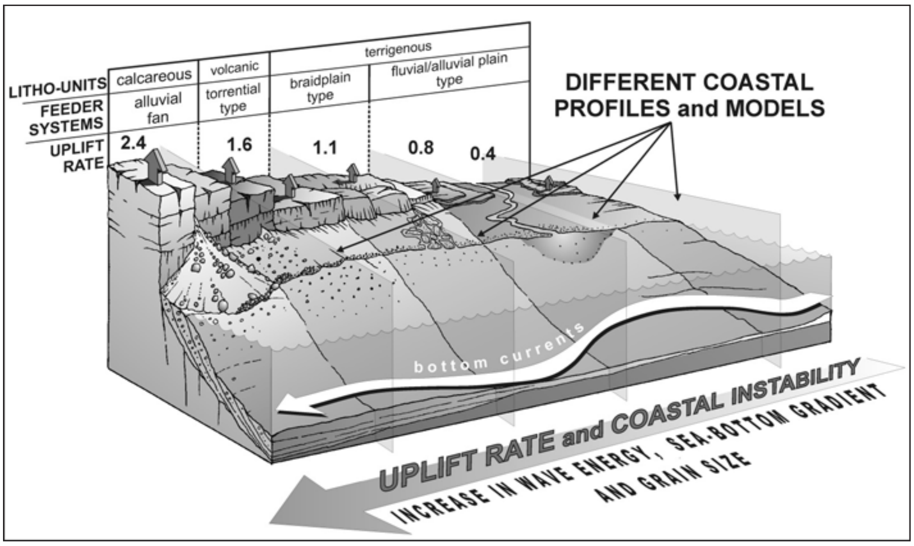

Fig. 17 - Some coastal profiles and models occurring along study coastline and related to changes in uplift rates. In this type of correlation, wave energy, sea-bottom gradient and beach sediment grain-size correspond directly to various classes of coastal vertical movements.

Diagramma che mostra alcuni differenti modelli costieri sono stati individuati lungo litorale studiato, in funzione della variazione dei tassi di sollevamento. In questo tipo di correlazione, l'energia del moto ondoso, il gradiente del fondale sotto costa e il diametro medio dei sedimenti corrispondono a differenti classi di movimenti verticali della costa.

meandering streams (Messina and Giardini Naxos) and then to alluvial fans (Riposto), directly influencing the beaches.

The vertical tectonic movements affecting the coastal bedrock strongly influence the sedimentation style of the supply systems and the morphology of the beach types which develop here show no influence of continental shelf morphology.

Correlations between the morphology and sedimentology of a beach type and the local uplift rate may thus represent a useful tool in discriminating behavior, and may perhaps be applied to other similar coastal systems. However, the model is hypothetical and needs to be verified by means of a wider range of case studies, like those represented by the beaches in the central-southern part of the Ionian coast of Sicily.

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