Sedimentary features of incipient beachrock deposits along the coast of Simeto River delta (eastern Sicily, Italy)

Sergio Longhitano

Dipartimento di Scienze Geologiche, Università degli Studi della Basilicata
Campus di Macchia Romana 85100 Potenza, Italy
E-Mail: longhitano@unibas.it

Abstract

The occurrence of beachrock outcrops along the coast of the Simeto River delta, the greater watercourse of Sicily, is described in this work. The delta is located into a microtidal context, where the wave energy action prevails on the coastal depositional processes as controlling factor. The deposits are constituted by discontinuous levels, 1-1,2 meters thick of very well cemented arenitic sediments of recent age.

The present human-induced changes of the precarious equilibrium regulating the sediment supply to the coast during last century, in the high part of the Simeto River drainage basin, caused strong erosion, with marked coastal land-loss examples. Because of that, the studied horizons have been quickly exposed from their original cover. As a consequence, they have been comprised into a vadose-freatic horizon, affected by percolation of meteoric and marine waters. Precipitation of calcite- and aragonite-rich solutions has determined their rapid cementation. For this reason, these discontinuous levels cropping out along the southern sector of Plaia di Catania beach are considered as recent incipient beachrocks *sensu* Kneale and Viles (2000).

Beachrock formation, principally due to strong erosional rates characterising the Catania coastal plain, is also attributed to the high tectonic uplift rate, which has affected the whole eastern margin of Sicily, at least since the Upper Pleistocene.

Keywords: Simeto delta; beachrock; human impact; sea-level changes; uplift.

Introduction

The Simeto River delta forms an irregular N-S oriented sandy shoreline 10 km long, located along the Ionian side of Sicily (Italy). The delta extends from the southern basaltic coast of Catania, formed by the 1669 eruptive event of the Etna active volcano, to the Agnone bay, where the calcareous Hyblean coast takes place. The Simeto River, running from Nebrodi Mounts, debouches into the Ionian Sea and develops its delta into the southern sector of the coast (Fig. 1).

The Simeto River delta coast is today formed by a very narrow very coarse to fine sand beach; its present *non-equilibrium* state shows a complex pattern of sub-environments, with local superposition. In fact, the relicts of the old dunefield cover locally the storm berm which, in turn, is extremely close to the swash berm (Photo 1).

Recent studies (Amore et al., 1992; Longhitano, 2000; Longhitano and Colella, 2001) demonstrate an high receding rate of the beach due to decrease in sediment supply and consequent erosional wave action along the coast of Catania. This exposed the oldest sandy levels of the beach, removing the primary cover of the present beach.

Locally, where the erosive action is strongest, discontinuous levels of consolidated sandy deposits, slightly inclined seaward, can be observed. The most complete outcrop can be observed close to Simeto River mouth, where the joint erosive action of the waves and river during the winter have exhumed the lower indurated levels of the beach.

Cementation of beach material, often producing a recognisable 'beachrock', is commonly found along the Mediterranean coasts (El-Sayed, 1988; Strasser et al., 1989; Holail and Rashed, 1992 – Fig. 2), characterised by different cement conditions and located into various geological settings. Numerous studies offer detailed descriptions for sedimentary and morphological features of different kinds of beachrock (e.g. incipient beachrock, supratidal or intertidal beachrock, cayrock, *etc*...), but only few authors provide a geological explanation for about beachrock formation. For example, Gischler and Lomando (1997) consider the beachrock deposits in Belize

Photo 1 - Panoramic view of the Simeto Delta northern shoreline. The Etna Mount in the background.

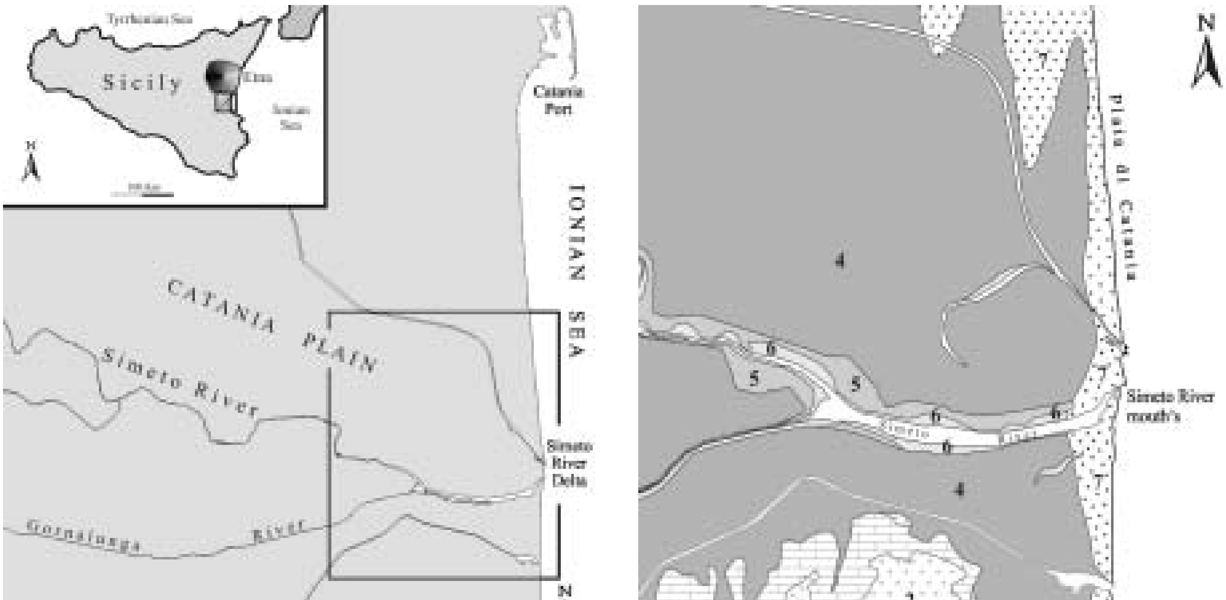

Fig. 1 - (A) Location of Simeto River delta. (B) Geological setting of the Simeto delta: Bedrock: 1 - Pliocene Calcarenites; 2 - Pliocene Volcanites; 3 - Pliocene Clays. Simeto Delta: 4 - Alluvial sands and clays (Holocene); 5 - Terraced fluvial sands and silts (Recent); 6 - Terraced fluvial sands and silts (Present); 7 - Beach (Recent and Present).

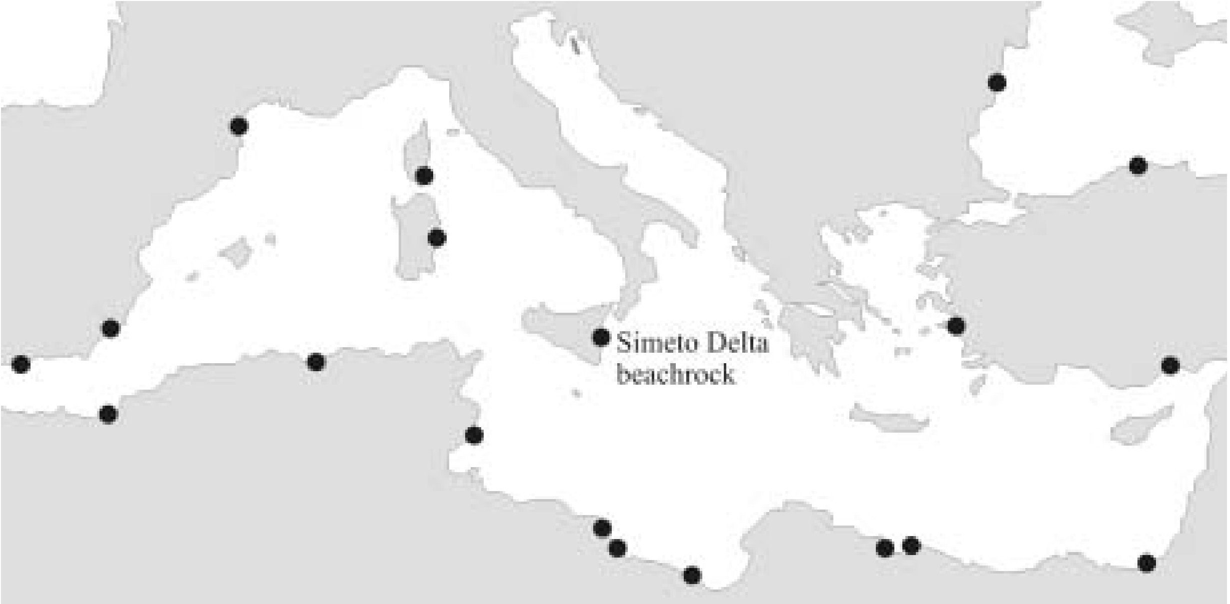

Fig. 2 - Main beachrock occurrences along the Mediterranean coasts.

as a response to sea-level changes or local tectonic movements.

The Simeto Delta beachrock is the first indication of beach cemented deposits for the Ionian coast of Sicily (Longhitano, 2001). In this paper, only sedimentary observations have been collected to describe them. The aim of this paper is to document the presence of beachrock deposits along the Simeto Delta shoreline as a consequence of human activity, and to suggest a possible relationship with local geological setting.

Previous studies on the beachrock formation

Since 1832, Charles Darwin describes some 'consolidated beach layers' in his "Geological Observations on the Volcanic Islands and Parts of South America Visited During the Voyage of HMS Beagle". Other descriptions of cemented beach deposits include those by Stoddart (1962), Clark (1968), and Roberts et al. (1973). An early designation for beachrock can be found in Friedman and Sanders (1978), who defined beachrocks as 'rocks formed by cementation of the sediments in the intertidal parts of beaches'. They adfirm that all modern beachrock are restricted to warm climatic belts, between latitudes 35ºN and 35ºS, suggesting that in addition to seawater supersaturated for $CaCO_3$, high temperatures within the beach sediments are necessary for cementation.

Cementation of beach sediment occurs at present day in several cases; this is confirmed by occurrence of pottery fragments, bottles and other human debris inside the beach sediment.

The process leading to a quick consolidation of intertidal beach sediment must be searched into the alternation of soaking by seawater at high-tide conditions and evaporation during low tide, leading to the physico-chemical precipitation of beachrock cement (e.g. Ginsburg, 1953; Davies and Kinsey, 1973; Krumbein, 1979; Scoffin and Stoddart, 1983).

Physico-chemical precipitation of beachrock cements was also proposed by Moore (1973), who suggests the importance of the mixing of marine and meteoric waters in the supratidal part of the beach.

Hanor (1978) concluded that marine-meteoric mixing cannot induce cementation, but that CO_2-degassing is a decisive factor for cementation of beachrock.

From a dynamic point of view, Strasser and Davaud (1986) showed that the formation of intertidal and supratidal cemented material occurs after beach accretion and progradation. Subsequent erosion exposes the consolidated rocks, and secondary intertidal cementation leads to beachrock formation.

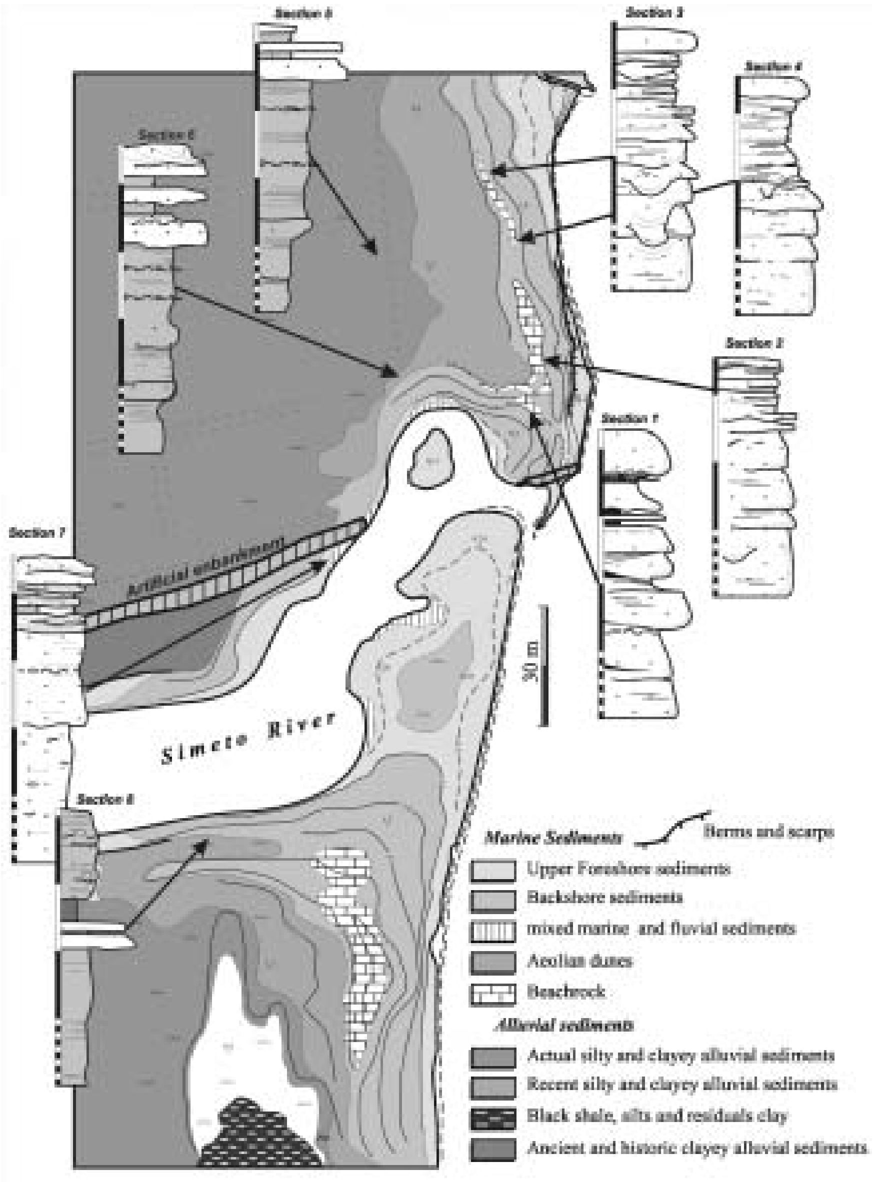

Fig. 3 - Lithologic map of the Simeto River mouth and location of measured sections. Note the distribution of beachrock outcrops.

Bain (1988) gives to beachrock an environmental significance, considering beachrock formations as a protection factor for beach erosion and for enhancing beach progradation.

Several authors emphasize the geological role of beachrock layers along a coast, in order to recognise recent sea-level fluctuations or recent tectonic uplift or subsidence (Beier, 1985; Kindler and Bain, 1993; Vollbrecht and Meischner, 1993; Gischler and Lomando, 1997).

A laboratory model has been recently developed by Neumeier (1999) to reproduce natural conditions of beachrock formation. This author confirms the significance of chemical (salinity, Ca, Mg, ΣCO_2, pH, $CaCO_3$ saturation) and physical features (temperature, evaporation, illumination) of sediment and suggests the importance of microbial activity during beachrock formation.

Finally, a condition in which beach sediments show discontinuous and small-scale cemented layers (especially at high latitudes) can be defined as 'incipient beachrock' (Kneale and Viles, 2000).

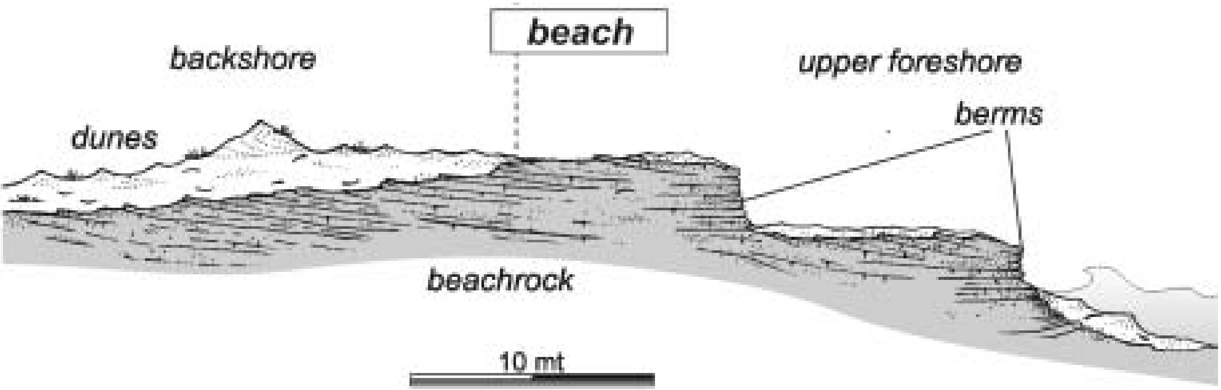

Fig. 4 - Schematic section through the Simeto Delta beachrock

The Simeto Delta beachrock

Description

Considering the microtidal marine regime of the Ionian Sea, the Simeto Delta beachrock cannot be classified as a *supratidal* or *intertidal beachrock* (Gischler and Lomando, 1997). As a consequence, only waves and, rarely, river current are important in sediment re-distribution along the delta coast (Longhitano, 2000; Longhitano and Colella, 2001).

Most of the Simeto Delta beachrock outcrops are represented by several ridges, tens of metres long, made up of several layers of beachrock, each up to 1-1,2 cm thick, gently inclined (<10º) seaward (Figs. 3 and 4; see also photos 2, 3 and 4). In most cases, the ridges are not wider than a few metres, but on the southern side of the Simeto Delta beachrock outcrops are up to 40 m wide. In some cases the dip of the beachrock cannot be deciphered, because of the limited outcrop area.

The discontinuous outcrops, their position along

Photo 2 - Northern side of the Simeto Delta beach. The arrows indicate the top of the incipient beachrock levels. The Simeto mouth in the background.

Photo 3 - Outcropping top of the beachrock along the southern side of the Simeto Delta. Note the aeolian sands covering the cemented layer.

a deltaic environment and the actual coastal retreat indicate a very low preservation potential for these sedimentary levels, due to the occurrence of reiterate erosive events (ordinary and stormy waves, fluvial overflows, coastal human activities).

Sedimentary features and beach cement

Sampling and logging of the cemented beach layers have been carried out at eight sites (Fig. 3). A mixture of siliciclastic and bioclastic sands forms the beachrock. Grain size ranges from very coarse-to-fine sand, with some very fine sandy volcanic lenses. Shells fragments and wood are abundant. The sand is moderately to very well sorted, and shows commonly an obvious lamination due to changes in grain size of constituent particles. These structures range from flat to low-angle laminations, but scour and ripples structures are also present. Palaeocurrents (laminae dipping and ripples) indicate a seaward range, but locally some high-angle landward-dipping foresets have been recognised.

Sedimentary structures allow recognition of five distinct sub-facies (see Table 1).

Photo 4 - Detail of photo 3.

	TYPE	SEDIMENTARY STRUCTURES	ABUNDANCE	CEMENTATION	HYDRO-DYNAMIC ZONE
Simeto Delta beachrock	sub-facies A	Flat and low-angle cross-laminated very coarse to medium sands with shell fragments.	35 %	high	*swash*
	sub-facies B	Low-angle cross-laminated coarse-to-medium sands with shell fragments. Frequent asymmetrical ripples.	15 %	scarce	*small tidal flat*
	sub-facies C	High-angle cross-laminated coarse-to-fine sands with wood detritus and shell fragments. Thin volcanic sandy layers interbedded.	20 %	very scarce	*washover*
	sub-facies D	Convoluted very-coarse sands with shell fragments. Scour structures.	10 %	medium	*storm berms*
	sub-facies E	Flat and low-angle laminated medium-to-very fine sands.	20 %	very high	*aeolian*

Table 1 - Sedimentary sub-facies of the analysed incipient beachrocks along the Simeto River Delta coast.

Sub-facies A and B are constituted by very coarse to medium siliciclastic and bioclastic sandy levels rich in shell fragments. The sedimentary structures are represented by prevailing low-angle inclined lamination alternated to some plain-parallel laminated beds. In the sub-facies B, often some asymmetrical ripple structures occur. The total thickness of these two sub-facies is 35-37 cm and the cementation rate changes upward from well to scarce.

The sub-facies C is constituted by sedimentary levels formed by coarse-to-fine sand in which the percentage of shell fragments and thin layers of wooden debris is most abundant than in the sub-facies A and B. High-angle-inclined laminated backsets are presently alternated with massive thin layers. The cementation rate for the sediment of this sub-facies ranges from scarce to very scarce, and the total abundance on outcrop is 20% of beachrock facies. Within the sub-facies C levels, some dark volcanic levels alternating to the beach sand have been recognised (Photo 5).

Very coarse-to-coarse sands, with a low percentage of shell fragments form sub-facies D. The main features are convoluted laminae and associated scour structures; The cementation rate of sediment of this sub-facies is medium and the abundance in outcrop is 10%.

Finally, the sub-facies E shows the presence of flat and low-angle laminated layers, constituted by medium and fine sands. The abundance is the 20% of the entire outcropping studied levels. Similar aeolian-cemented layers have been described also by Roberts et al. (1973) for dunes around the shores of NW Scotland.

The sedimentary facies recognised for Simeto incipient beachrock represents the emerged sector of a beach face (backshore and upper foreshore), indicating the presence of swash, small tidal flat and washover hydrodynamic zones.

The sedimentary structures associations indicate the transitional side of the beach, from upper foreshore (swash zone – sub-facies A) to lower backshore sub-environment (small tidal flat – sub-facies B), where sediment is re-worked by the ordinary wave action and, sometime, some small tidal currents are generated.

The shell fragments occurrence onto the beachrocks can be observed in the present beach, in which storm waves action leads to accumulation of this material in the lower backshore, at the end of high-energy events. High-angle-inclined laminated backsets indicate the presence of a washover hydrodynamic zone, where landward-dipping foresets are made by the effect of periodic stormy waves.

The intercalation of volcanic very fine sands to the present beach sediment is due to the neighbouring Etna volcano explosive activity (Photo 5). In this case, abundant volcanic fine sand is put in suspension up to some tens of kilometres far from the eruptive centre, and then deposited for fall-out. Although such phenomenon can represent an interesting geological topic, it could cause momentary troubles for human activities (e.g. impracticable air- and land-ways, crashing of the

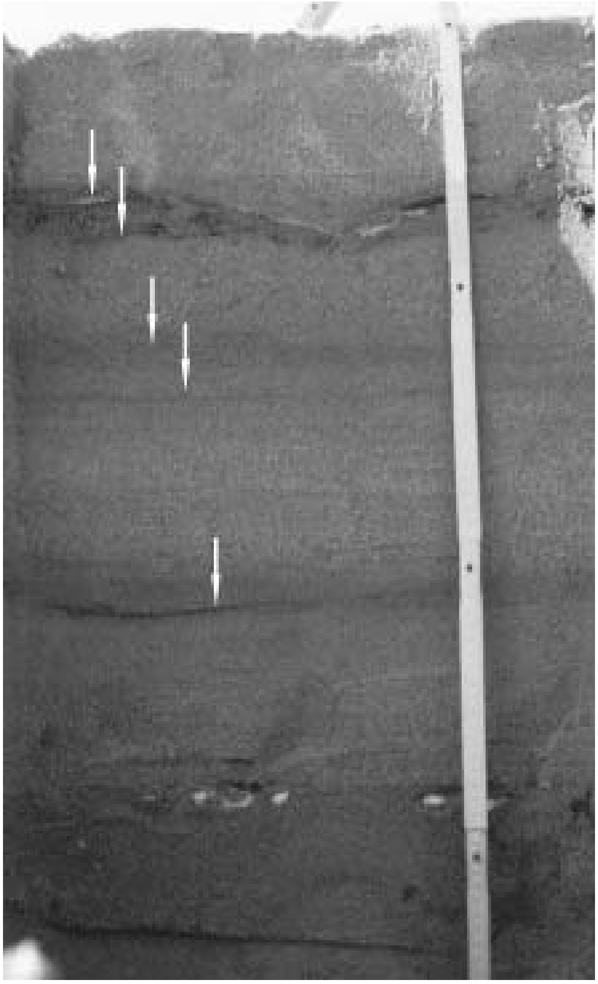

Photo 5 - Sub-facies C. The presence of volcanic thin layers (arrows) interbedded with cemented flat and cross-laminated sands can be noted.

refreshing systems, pollution of swimming pools). The volcanic levels recognised on the beachrock sediments thus represent the sedimentary record of the interaction between volcanic and coastal processes during the recent past, and can be considered as a good tool for an absolute dating of the Simeto Delta beachrock.

Convoluted laminae and scour structures, typical of a lower backshore sub-environment, are made up by the effect of storm waves reaching the storm berms. Flat and low-angle laminated layers of the sub-facies E represent the relict of the lowermost dunefield with incipient traces of induration (the cementation rate is very high).

In the small-scale stratigraphic succession (Fig. 5) the upper foreshore sub-facies (zone of swash, backswash, and small tidal flat) constitute the lower stratigraphic interval of the sections, reaching the total thickness of 1 m; the backshore sub-facies (washover, storm berm, and aeolian zone) are instead located at the top of the sedimentary levels. The beachrock succession then evolves upward from the external to most internal beach face, indicating a seaward shifting of the beach sub-environments. This migration of beach sub-facies could records sea level small-scale oscillations and/or uplift movement of the lower coastal plain.

As many other authors have affirmed about various beachrock occurrences for Mediterranean sites, the induration of beach sediment located into a freatic-vadose zone is quicker than other cases. In this context, reiterated infiltration of meteoric- (during the ordinary waves movement) and marine- (during the storms) waters produces the percolation of Calcite- and Aragonite-rich solutions. This condition is favoured especially where beach sediment is characterised by abundant occurrence of shells fragments.

In the cementation process an important role is played by the clima; in fact, also the seawater composition, its salinity and the CO_2- $CaCO_3$ saturation, the temperature and the illumination rate regulate the beachrock formation.

Previous studies about beachrock induration affirm that the presence of a bioactivity of microorganism populations is the main controlling factor for cementation process (Buczynsky and Chafetz, 1991; Neumeier, 1999), producing a biomineralization of interstitial solutions.

In these physic-chemical conditions, a laboratory model demonstrates that it is possible to obtain an incipient induration for beach freatic-vadose sediments only in few tens of years (Neumeier, 1999).

For Simeto Delta beachrock, all these factors are emphasized by Mediterranean clima and referable to other Mediterranean beachrock occurrences.

The chemical parameters have been obtained by the analysis of beachrock interstitial-water and then compared to parameters of main Mediterranean beachrocks. Therefore, the temperature of solutions ranges between 23º and 29º C, the salinity is comprised between 40.5 and 41.5 ‰. The pH concentration measured *in situ* is 8.0-8.1, the Ca concentration is 470-540 ppm and the ΣCO_2 ranges from 2.0 to 2.6 mmole/l (Longhitano, 2000).

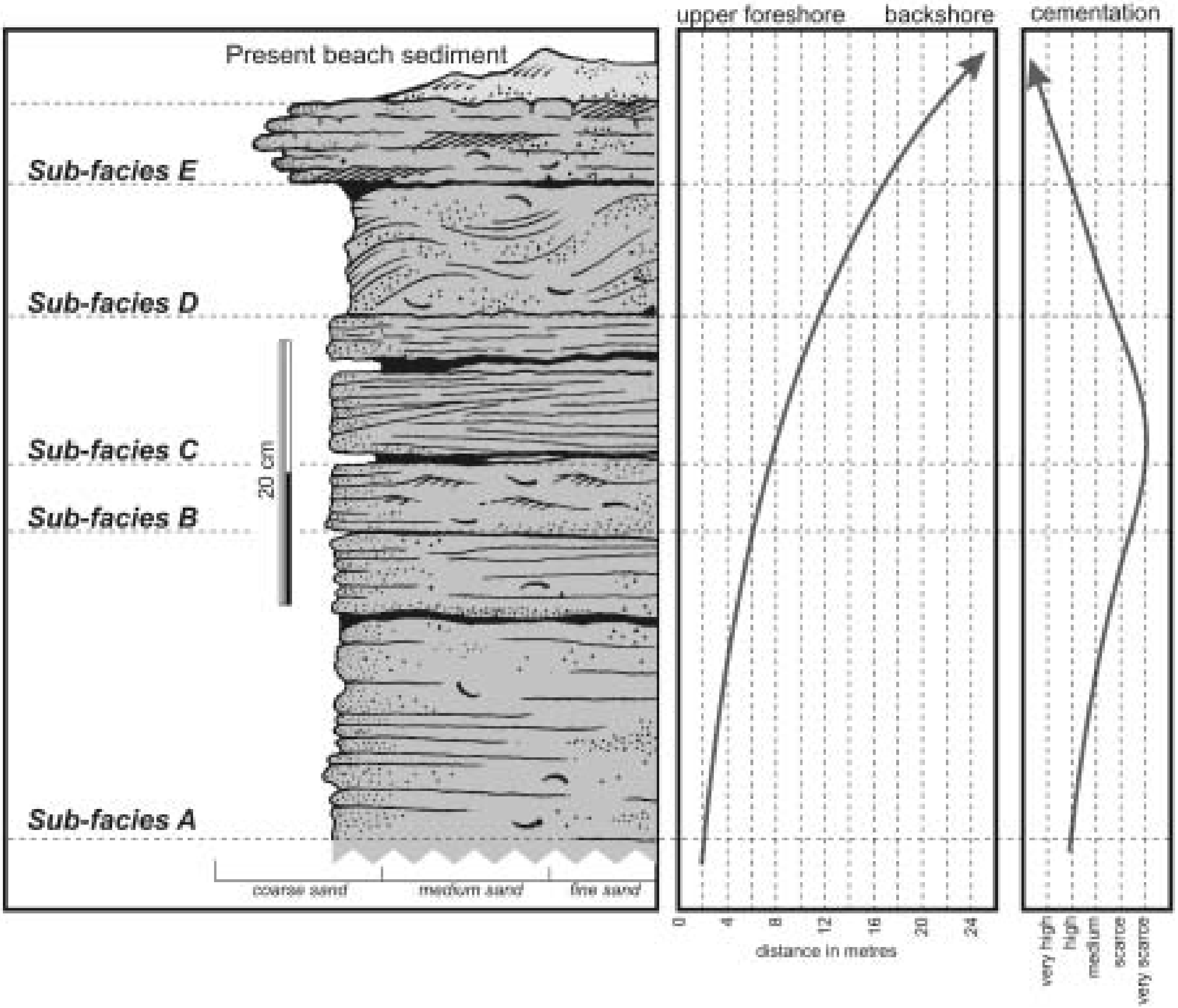

Fig. 5 - Summarizing log of Simeto Delta beachrock sub-facies compared with relative distance of each sub-facies from the present sea-level and estimation of sediment cementation rate.

Discussion

In previous work most authors define a recent or historic age for beachrock formation (Beier, 1985; Kindler and Bain, 1993; Vollbrecht and Meischner, 1993; Gischler and Lomando, 1997). This implies that the cementation can occur also long time after sediment deposition. The age of similar cases (Belize, North Uist, Alexandria, Dushit el Dabaa) ranges from BC 345 and AD 1435.

In other cases, the age of the beachrock deposition and formation is instead much more recent; some beachrock levels recognised along the Pacific coasts were in fact dated back to the World War II, for presence of 'war debris' within the sediments. Several cases (eastern Mediterranean and Caribbean beachrocks), pottery fragments, coca-cola and rum bottles confirm that cementation is occurring even at present (Friedman and Sanders, 1978).

For Simeto Delta beachrock we did not carried out absolute dating, but in some cases it was possible to observe the occurrence of blocks of etnean basaltic volcanites within the sediment (see photo 6). Neglecting any provenance by fluvial transport because of very low roundness of the clast outlines angular, we can form the hypothesis that these findings could represent the fragments of an artificial barrage, located at short distance

Photo 6 - Outcrop of Simeto Delta beachrock showing the presence of a volcanic (basaltic) block within the well-cemented sandy sediments (arrow). The section is located near the fluvial embankment, built in the 1950 and constituted by the same material of the fragment. These findings can represents a first approach to the dating of these incipient beachrock levels (see text for explanation).

Photo 7 - Panoramic view of the Simeto River delta forming a mouth gulf. The black arrows indicate the artificial fluvial embankment, built with aim to constrain the seasonally flooding of the river, and partially eroded during last 10 years by the waves powerful action. Note the black basaltic blocks constituting them.

from the study section. An embankment constituted by basaltic blocks and very similar to the fragments included within the beachrock, was built in this sector in 1950, with the aim to regulate the seasonal flooding of the Simeto River (Photo 7). Probably, the subsequent erosional action of the frequent marine storms could have partially destroy at the front of this barrage, producing detritus of basaltic blocks falling down into the beach sediment below.

Therefore, the sedimentation of the levels containing the lavic fragment could date back to about 50 years ago, and the cementation of such deposits could have occurred in an exceptionally short time.

According to other authors and considering that these deposits represent an early phase of beachrock development, for its high cementation rate, the Simeto Delta beachrock can be classified as an 'incipient beachrock' or 'beach cemented'.

The percentage of calcite and aragonite of the solutions infiltrating the sediments can have reached high value of concentration due to the abundance of mollusc shells, which contributed to accelerate the induration of the beachrock.

The quick denudation of the sector by the local erosional rate, together with reiterated stage of percolation of meteoric and marine waters, concurred to this drastic vadose-phreatic cementation.

The quick erosional rates that characterise the Simeto Delta shoreline and the entire Ionian coasts should be attributed to human activity during the last 50 years in the area of Simeto River. Accelerated erosion of the Simeto deltaic coast is attributed i) to the emplacement of four dams along the course of the river, ii) to the destruction of dune ridges and their vegetation, iii) to the emplacement of maritime and protection works, and iv) to uncontrolled withdrawal of sands and gravels from riverbeds and beaches. This caused a quick decrease in sediment supply, accentuated by reduction of annual meteoric precipitations, inducing a strong environmental impact onto the whole coastal plain of the Simeto delta plain (Fig. 6). This is mainly due to the lack of territorial planning of human constructions and of coastal management programs in this area.

Therefore, the denudation of lower sedimentary beach levels because of land-loss coastal regime has been fundamental for the present incipient formation of the Simeto Delta beachrock. The presence of these sedimentary levels can be considered as a consequent natural process onto the coast triggered by uncontrolled human activities.

The occurrence of vertical changes in stratigraphic position of the beachrocks sub-facies (common in both backshore and upper foreshore) suggests that the Simeto Delta beachrock deposits evolved during a short oscillation of sea level or contemporaneously to small vertical movements of the costal plain.

As mentioned above, beachrock occurrences were in several cases used to decipher Quaternary changes in sea-level (e.g. Beier, 1985; Kindler and Bain, 1993; Vollbrecht and Meischner, 1993; Gischler and Lomando, 1997). Stratigraphic features of the Simeto Delta beachrock, suggest a relative sea level variations. In fact, the sedimentary sub-facies pertaining to the upper foreshore beach face occupies the lower interval of the beachrock succession, and evolves upwards to more internal sub-facies, relative to the backshore beach face. This abrupt variation can be due to a small-scale sea-level fall. The comparison of historic pictures of Catania coastline during the '20s (Photo 8), shows presence of the sea where today an urban street (*Via Archi della Marina*) is located. This suggests a non-quantified possible sea-level fall during the last century. In this case, however, the amount of the sea level falling should represent a too high value for a small-scale sea-level oscillation in the late Holocene (Jedoui et al., 1998). Therefore, we must find an additional factor to explain the Simeto Delta beachrock incipient formation.

Several studies demonstrate that the Ionian coast of Sicily has been characterised by high uplift rates at least since 200 ky BP (Cosentino and Gliozzi, 1988; Firth et al., 1996; Monaco, 1997; Bordoni and Valensise, 1998; Rust and Kershaw, 2000, Di Stefano and Branca, 2002). The uplift rates, documented for this sector by the abovementioned Authors ranges from 0.2 to 2.0 mm/y. These values have been estimated from Holocene terraced surfaces and marine notches and sediments located along the Ionian coasts of Sicily and Calabria.

The collected dataset shows a lack of uplift measurements just in coincidence of the Catania Plain coast, because along a present alluvial-coastal plain it was not possible to recognise any data to decipher Quaternary tectonic traces of vertical movements.

The quick uplift that characterised the studied

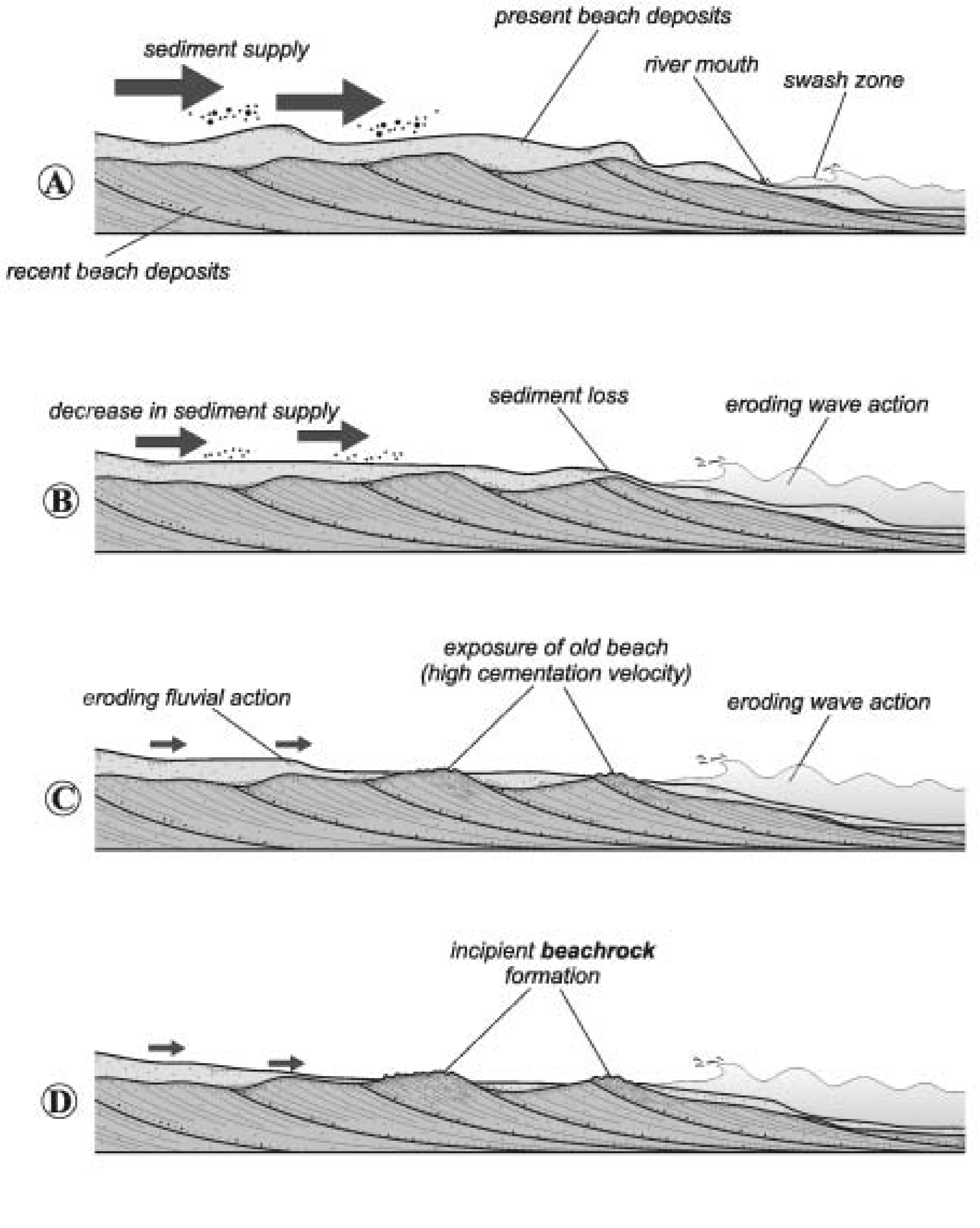

Fig. 6 - Model showing the role of the denudation of the lower beach deposits caused by decrease in sediment supply along the Simeto Delta shoreline and consequent erosion by waves attack (after Longhitano, 2001).

Photo 8 - Historical and present picture of "Via degli Archi della Marina" along the eastern marine side of Catania during 1900. This sector is located 8 km north of the study area.

area in the past must be still active today, and should have strongly influenced the formation of the incipient Simeto Delta beachrocks, contributing to the formation of small-scale depositional architectures of these levels and emphasizing the changes in the sedimentary sub-facies.

Conclusions

This paper documents for the first time the occurrence of beach cemented deposits along the Ionian coast of Sicily. Stratigraphic and sedimentologic analyses of these sedimentary layers cropping out along the Simeto Delta coasts point out the following conclusions:

1. the formation of beachrock deposits should primarily be attributed to quick denudation of the Simeto Delta beach, because of the strong retreating of the coast. Such condition represents a consequence of an uncontrolled human activity in this sector;
2. the sedimentary features of the sub-facies constituting the Simeto Delta beachrock deposits indicate the presence of several depositional sub-environments representing the upper foreshore and the backshore beach face;
3. the age of these deposits cannot be estimated, but the presence of some basaltic blocks inside the beachrock sediment, deriving by the erosion of a neighbouring artificial embankment, can induce to consider themselves not much older than 50 years.
4. the presence of a vadose-freatic zones including these levels, the richness of skeletal rests and other favouring chemical-physical factors (e.g. temperature, illumination, salinity, CO_2-$CaCO_3$ saturation, etc...) represent the best conditions for beach sediment induration and are considered fundamental to explain the very young age of these beach cemented layers;
5. considering its very young age and its small-scale (incomplete?) cementation, the Simeto Delta beachrock represents an 'incipient beachrock';
6. the vertical succession in the sedimentary sub-facies shows the presence of the most external hydrodynamic zones (swash and small-tidal flats) in the lower part, passing abruptly to the most internal ones (washover, storm berm and aeolian dunes). Such evolution suggests two possible hypotheses: a small recent sea-level fall and/or a contemporaneous uplift of the entire coastal area;

The occurrence of beachrock deposits then can be considered as a good indicating factor for the beach preservation state, for present small-scale sea-level oscillations and for local tectonic uplift movements.

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