2020 IMEKO TC-19 International Workshop on
Metrology for the Sea
Naples, Italy, October 5-7, 2020

The present-day nearshore submarine depositional terraces off the Campania coast (South-eastern Tyrrhenian Sea): an analysis of their morpho-bathymetric variability

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***Abstract* – A census of about 76 near-shore Submarine Depositional Terraces (n-SDT) has been realized along the Campania offshore, in order to verify the correlation of their edge depths versus their fetch - used as a proxy of the wave forcing- at a regional scale. The main morphometric parameters of each terrace were derived from high resolution Digital Elevation Models (DEMs), by means of a GIS-based software. A moderate correlation occurs between the edge depth and the geographical exposure of all the n-SDTs and it improves if the NW- oriented terraces only are considered; the best correlation is observed with the edge depth of the n-SDT developed around the rocky cliffs and promontories. A complementary analysis of the extreme wave climate in the area, in relation with the edge depth of n-SDTs, was also carried out. The aims of this study are to learn more on the morpho-bathymetric variability of these coastal bodies and to provide clues on the use of their past counterparts as morphological proxies of past sea level stands.**

I. INTRODUCTION

Nearshore Submarine Depositional Terraces (n-SDTs, [1]), otherwise named Infralittoral Prograding Wedges (IPW, [2]) or Delta-scale Subaqueous Clinoforms [3], are depositional coastal bodies with internal clinoforms sloping basinwards, growing beyond the lower edge of the shoreface [4]. They have been developing since about 6-5 ky BP, when the sea-level has attained the present-day position (+/- 1 m) [5]. These bodies typically form on the inner shelf under the combined action of storm waves and across-shore currents, which redistribute littoral or fluvial sediments below the depth of closure and are bounded by a sedimentary bypass surface at their top [3,6]. The depth of the SDTs edges depends on a complex interplay of several factors, such as the local storm wave base, the coastal physiography, the sedimentary balance of the coastal area and, eventually, the amplitude of the recent vertical ground movements.

In this study we have analyzed a large number of n-SDTs, occurring along the south-eastern Tyrrhenian coast, to identify the controlling factors which may have affected their distribution and to test their reliability as environmental indicators of water depth. As a matter of facts, their ancient counterparts have been used as marine geomorphic/sedimentary markers for earlier and lower sea-level stands [7-9].

II. DATA AND METHODS

This study makes use of a regional-scale marine DEM, made up of a composite data set, with a minimum grid cell of about 20 m, acquired over the last twenty years by IAMC-CNR, now ISMAR-CNR.

A number of 76 n-SDTs lying around Capri, Ischia and Procida islands, and along the coasts from the Gaeta to the Policastro gulfs (Fig.1) has been analysed. The data set includes the rollover point depth (ROD) - i.e. the break-in-slope depth between topset and foreset - the geographical exposure (fetch) and the coastal orientation of each n-SDT, measured by means of a GIS-based software (Global Mapper ®). The coastal physiography behind the n-SDTs has been also taken into account and four coastal morpho-types have been distinguished: rectilinear rocky cliff, rocky promontory, inlet/pocket beach and open-coast shoreline [10]. This study is based on the experimental observations of the relations between the ROD, the geographical orientation, the coastal morpho-types versus the fetch, here considered as the geographical limit of the wave generation areas along a single direction at right angles to the coastline. The local wave storm climate has been also included in the analysis.

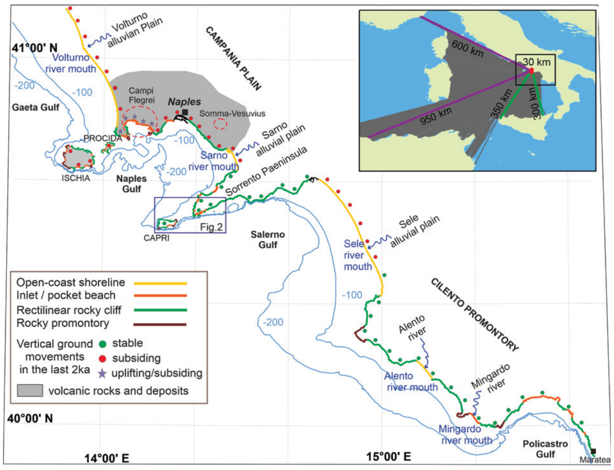

Fig. 1. Coastal morpho-types in the study area. The inset shows the location of the study area and the three main cluster of fetches with respect to the Campania region coasts

The main idea of this procedure is that the geographical fetch (GF), here considered as the geographical limit of the wave generation areas along a single direction at right angles to the coastline; it determines the sea response to meteorological forces, depending on the wind direction [11]. In other words, the GF is used as an index of wave forcing acting along the inner shelf. However, such assumption may fall short. In fact, sites with the same orthogonal fetch extension, and under the same perturbation, can experience very different extreme waves according to the energy dissipation, due to local bottom friction and wave-breaking, and other site-specific wave phenomena. That is what happens for the Campania Region coasts: despite longer fetches facing the Algerian, Tunisian and (in some cases) Sicilian coasts, more than 45% of the annual offshore wave energy comes from the sector 260-320° N [12]. This is due to the mesoscale climate conditions, with swells approaching from distant storms coming from the NW sector of the Mediterranean Sea. Therefore, to better identify the correlation between the ROD of the south-oriented n-SDTs and the wave hydrodynamic during severe storm condition, a numerical study of the near shore wave pattern has been carried out. To this purpose, the numerical coastal propagation model (Mike21 SW) has been adopted [13]. The computational domain was discretized using an unstructured triangulates mesh. The reference bathymetry at grid nodes was interpolated from a gridded bathymetrical data set provided by General Bathymetric Chart of the Ocean [14] with a resolution equal to 30" of arc. Wave input data have been supplied by the directional buoys operating offshore in Ponza (central Tyrrhenian Sea, 40°52′0.10″ N; 12°57′0.00″ E) actives since July 1989 as part of the Italian Buoys Network [15]. The data set comprises the spectrum zero-moment wave height (Hm_0), the mean period (T_m), and wave direction (θ_m). The geographic transposition has been applied in the form described for instance by Contestabile et al. [12].

According to current coastal engineering practice, extreme wave events are described in terms of the function $H_S(T_R)$, which links the significant wave height (H_S) of a sea state with different return periods T_R [16,17]. The selected value of T_R is 200 years, a time span considered long enough to be representative of the environmental conditions over the last 2 ky, and at the same time, compatible with the length of the original time series used to perform the statistical analysis. To produce a set of extreme significant wave height values, the Peak Over Threshold (POT) method was followed, adopting a Generalized Pareto Distribution.

III. GEOGRAPHY AND COASTAL MORPHOLOGY

The Campania region coast, entirely facing the South-eastern Tyrrhenian Sea, is about 480 km long. It displays a variable topography for the occurrence of volcanic areas, islands and NE-SW-trending headlands (Sorrento Peninsula and Cilento Promontory), which bound the main morpho-tectonic depressions of the Campania and Sele Plains (Fig. 1).

The low open-coast shorelines characterize the seaward edge of the main alluvial plains -Volturno, Sarno and Sele rivers, respectively – facing the gulfs of Gaeta, Napoli and Salerno.

The rocky coasts bound seawards the volcanic areas (Ischia Island, Campi Flegrei and Mt. Somma-Vesuvius) and the main morpho-structural reliefs (Capri Island, Sorrento Paeninsula, Cilento) by alternating high promontories, small inlets and rectilinear cliffs. The small inlets commonly held pocket beaches, characterized by coarse loose sediments.

IV. PRELIMINARY RESULTS

The general shape of the n-SDT bodies is convex upwards in shore-normal profile and convex-seaward in plan-view (Figs. 2a and 2b). They are continuous and elongated prisms, extending hundreds of meters up to kilometers in the shore-parallel direction and are several meters thick. The ROD ranges from -10 m to -37 m.

A remarkable difference in size and shape comes out between terraces off the rocky and open-shore coastlines (e.g. at river mouth). In the first case, they develop basinward for few hundreds of meters, show distinct offlap breaks and slope angles ranging between 4° and 20° [18]. In the second case, they extend much longer from the shoreline (2-5 km) - as expected due to the fluvial particle yield –, show much smoother offlap breaks and slope angles not exceeding 2°-3°. Actually, off the river mouths (Volturno, Sele, Alento, Mingardo and Bussento rivers, Fig. 1) the terraced surfaces correspond to the subacqueous delta top and the foresets to the subacqueous delta slope in the prodelta environment [3,19,20]. We observe that the besides these two extremes, an in-between category occurs off the main high-gradient streams along the rocky coasts, where intermediate-sized n-SDTs may be observed, shaped on small-sized fan deltas [21].

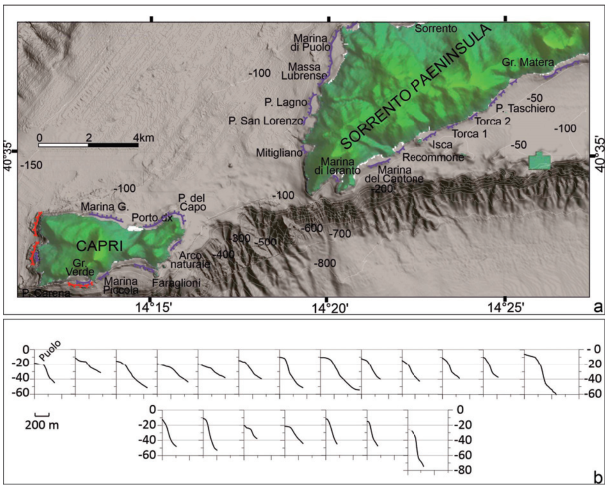

Fig. 2. a) Location of the n-SDT (present-day terraces in violet, ancient terraces in red) around the Sorrento Paeninsula and Capri Island, a stable area since the last 100 ky [22]; b) topographic profiles of the n-SDTs.

A. General relation ROD/Geographical fetch

The first analysis plots the ROD of each n-SDT versus the length (km) of the GF), regardless the orientation of the terraces. A general direct correlation can be observed and R^2 is moderate (0.42). Therefore, as a general observation, the terraces grow deeper with the increasing length of the waves generation area. However, the correlation increases to $R^2 = 0.45$, if the n-SDT oriented towards the South are excluded from the analysis (Fig. 3a).

Three clusters can be observed in the general plot (marked in red, green and violet circles); they are linked to the geographical outline of the coast, which confines the fetch of the n-SDT. The first cluster at about 30 km along the X axis corresponds to the geographical barrier of the coasts of the Napoli Gulf and of the islands which limits the fetch of the NW-, SE-, NE- oriented n-SDTs lying in the Napoli Gulf itself; the cluster at 300 km along the X axis is linked to the Calabria-Sicilia geographical boundary with respect to S- and SE-oriented n-STDs of the Napoli and Salerno gulfs; the third cluster at about 500-600 km along the X axis is represented by the geographical boundary of the Algerian-Tunisian coast with respect to the SW-oriented n-SDTs and of the Liguro-Provencal coast with respect to the ones oriented towards the NW (Fig. 1).

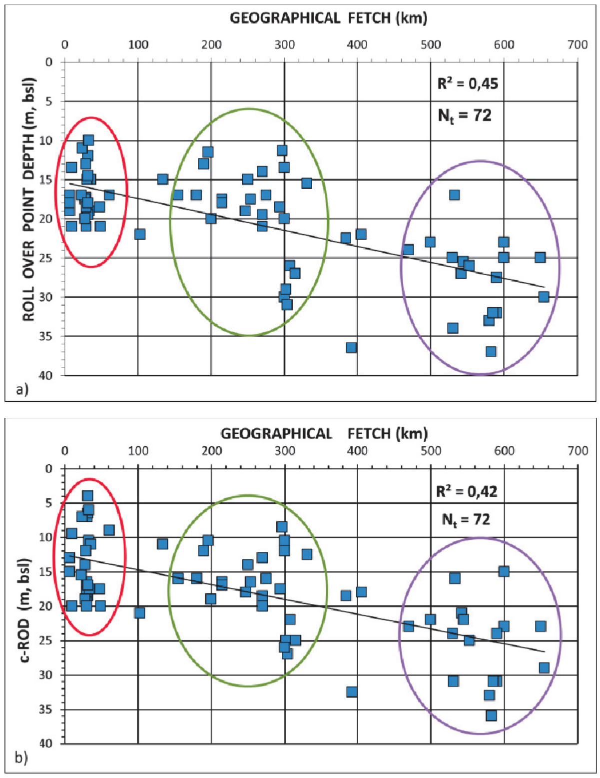

*Fig. 3. General correlation between **a)** the measured depth of the rollover point (ROD) and **b)** the corrected depth (c-ROD) versus the geographical fetch for each terrace. The three clusters group the geographical fetch of the n-SDT, confined by the Napoli Gulf (red circle), Calabria and Sicily coasts (green circle) and Tunisia and Liguria coasts (violet circle).*

Given the different vertical ground movements of the coastal sectors off the Campania region in the last 2 ky [23-27], a correction mainly derived from the submerged archaeological remains to the measured ROD has been tentatively applied to verify the impact of the fast relative sea-level changes on these coastal bodies. Actually, the n-SDTs on fast subsiding coastal areas may result as slightly displaced to depth where the erosive-depositional processes associated with the storm-waves action might be not able to compensate the volcano-tectonic movement. This could be the case of the Campi Flegrei and Ischia Island coastal areas, where the high rates of subsidence are mainly testified by the submerged archaeological remains of Roman age [23, 24,26,28]. The outcome of this test shows that the correlation index worsens to $R^2 = 0.39$ if a corrected ROD (c-ROD) is considered for the terraces lying in the fast-subsiding areas and to $R^2 = 0.42$ by excluding from the dataset the south-oriented n-SDTs subset (Fig. 3b). This comparison suggests that the vertical ground movements in the study area are almost ineffective in the process of n-SDTs evolution.

B. Relation ROD/geographical fetch for specific n-SDT orientation

The correlation between ROD and GF for the n-SDTs grouped according to their orientation shows contrasting results: R^2 is almost null for the terraces exposed to the 0°-90°N sector and 0.19 for those exposed to the 90°-180°N sector; the correlation increases to about 0.28 in the subset of the 180°-270°N-oriented terraces and to 0.76 for those 270°-360°N-oriented (Fig. 4). An inverse correlation with $R^2 = 0.53$ is observed between ROD and GF for the S-oriented terraces subset - i.e. the longer the fetch, the shallower the ROD - and it has no logical explanation, so far. This is the reason why the general correlation in Fig. 3 improves by excluding the South-oriented n-SDTs.

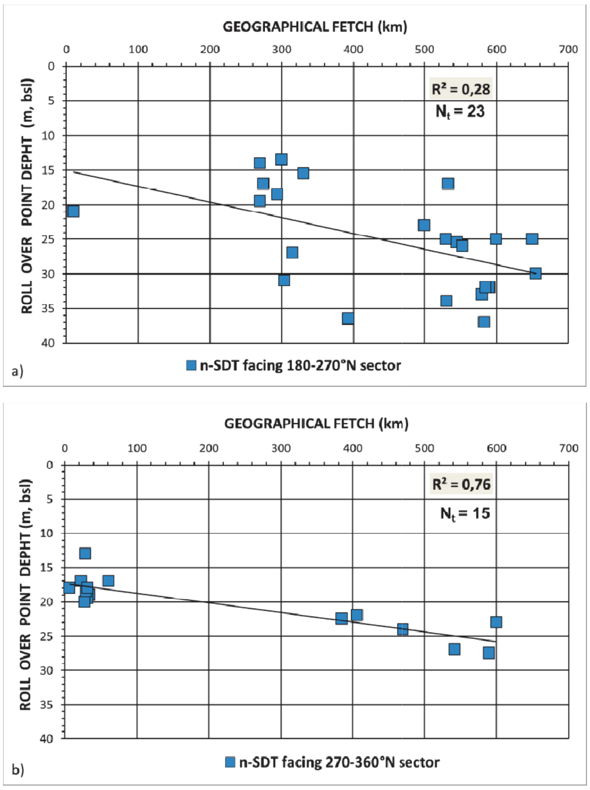

*Fig. 4 Cross-plot of ROD versus geographical fetch of the **a)** SW-oriented n-SDTs **b)** NW- oriented n-SDTs. The clusters group the n-SDTs confined by the Calabria-Sicilia and by the Tunisia coasts in **a)** and by the Napoli Gulf and by the Liguria coasts in **b).***

C. Relation ROD/geographical fetch for specific coastal morpho-types.

The analysis of the n-SDTs grouped for the different morpho-types of the coast (inlet, promontory, rectilinear rocky cliff, open-coast shoreline) shows a moderately good correlation for the first three subsets (R^2 = 0.36, 0.56, 0.49, respectively, Fig. 5) and an inverse correlation, with R^2 = 0.73, for the last one, possibly biased by the low number of terraces and by the comparable GF, almost in the same range (290-300 km).

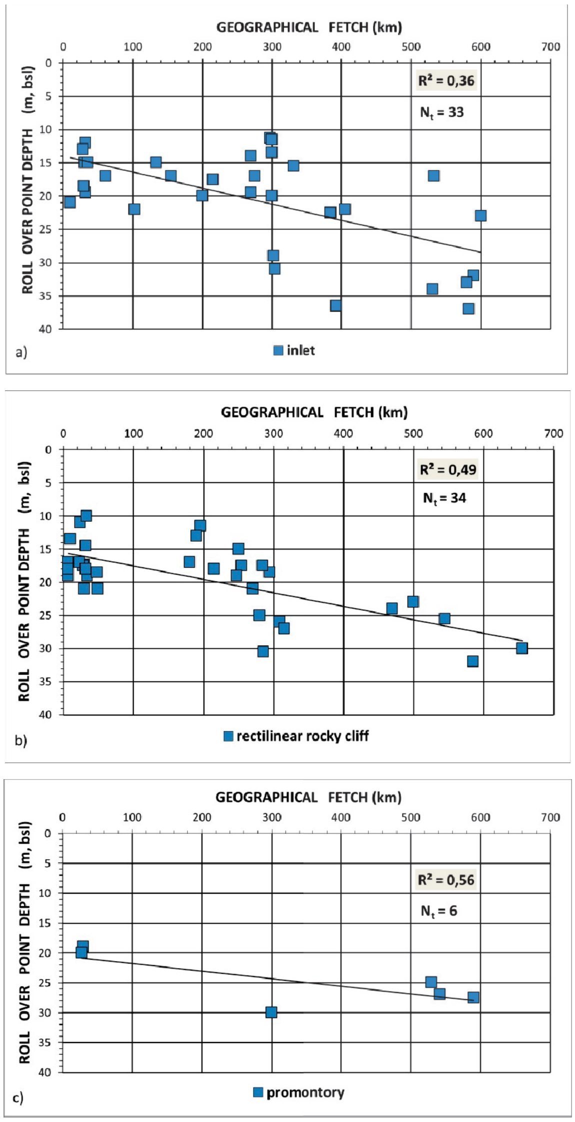

Fig. 5. The ROD versus GF for each morpho-type subset displays R^2 ranging from 0.36 to 0.56.

It is possible to infer that in the areas where the yield of fine sediments is particularly high - as for the open-coast shorelines bounding the alluvial plains - the influence of the fluvial processes prevails over the storm-wave climate and thus the fetch length turns to be not relevant. On the contrary, in the coastal sector where the fine-sediment availability in the shore system is limited - as in the case of the n-SDTs formed around the promontories, rectilinear rocky cliffs and off the isolated inlets - the morphological action of the storm wave regime on the long term is more effective in transferring sediment across-depth and the fetch length of the terraces is a relevant factor in their development through the time.

D. Preliminary analysis of relation ROD/extreme significant wave heights.

The analysis of the offshore wave data for the south-oriented n-SDTs of the Campania region has allowed the identification of three directional wave sectors (i.e., 70-190° N; 190-250° N; 250-320° N), each with their own "200-year" wave height (6.5 m, 8.3 m and 10.8 m respectively). The resulting eleven extreme sea states scenarios, including the correspondent peak wave period (T_P), are reported in Table 1. The "input" offshore wave directions (θ_m) as propagated by applying the MIKE 21 SW, are also reported. An example of numerical result of wave propagation is graphically represented in Fig. 6.

Table 1. Simulated sea state scenarios.

H_S [m]	T_P [s]	θ_m [°N]
10.8	14.1	320
10.8	14.1	285
10.8	14.1	250
8.3	12.4	240
8.3	12.4	215
8.3	12.4	190
6.5	11	175
6.5	11	140
6.5	11	105
6.5	11	70

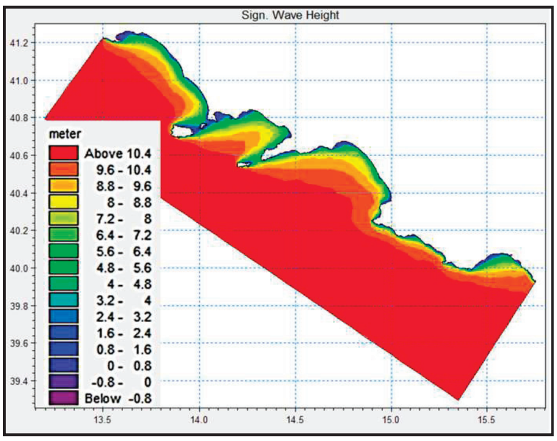

Fig. 6. Example of wave propagation (H_S=10.8 m; T_P=14.1 s; Direction 250°N).

Preliminary results on the relation between the maximum local significant wave height (detected under the aforementioned sea state scenarios) and RODs for the South-oriented n-SDTs subset are displayed in Fig. 7. A very good relationship, which can be adequately represented by a logarithmic law, with R^2 higher than 84% has been found. Therefore, a heuristic explanation of the inverse relation ROD versus GF in the South-oriented terraces subset could be proposed. Based on the previous observations of high reliability offered by the local extreme H_S assessment, it is suggested as the use of the fetch as wave forcing indicator could lose its efficiency in some conditions.

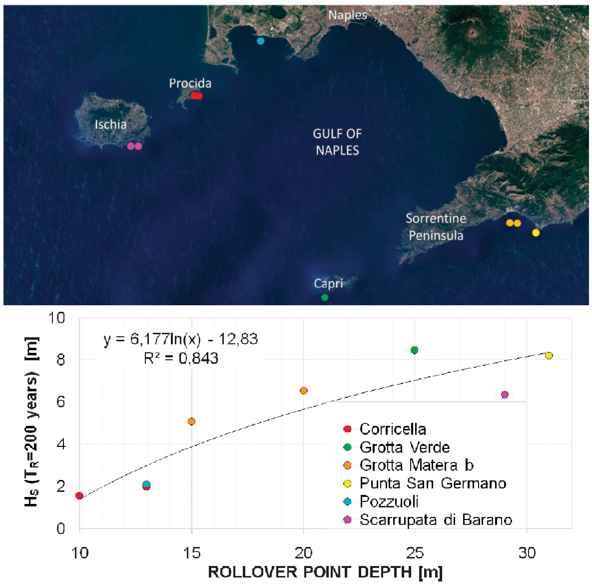

Fig. 7. Correlation between ROD and maximum local "200-year" significant wave height for the South-oriented n-SDTs subset.

V. PRELIMINARY CONCLUSIONS

A census of 76 n-SDTs along the Campania offshore has been accomplished, in order to verify the correlation of their depths (ROD) against their geographical fetch (GF) - thus indirectly versus the storm wave climate - at a regional scale. The analysis of key parameters used in this study, suggests that:

- the n-SDTs in the south-eastern Tyrrhenian Sea have extremely variable lateral extensions (from tens of meters to kilometers) and variable ROD (ranging from -10 m to -37 m); a slight variation in depth can be observed within the same terrace, especially where the coastal morphology in the background suddenly changes;
- a moderate correlation between ROD and the GF occurs (R^2 = 0.42) even if the typology of coastal morphology is overlooked; the coefficient improves to R^2 = 0.45 if the South-oriented terraces are excluded from the analysis;
- the most responsive n-SDTs to the GF variation are

those facing the 270°-360°N - oriented sector;

- the subsets inlets, promontories and rectilinear rocky cliffs ($0.36 \leq R^2 \leq 0.56$) are the most responsive to the variation of GF; the inverse correlation observed between ROD and GF in the open-coast shorelines subset suggests that the effects of the fluvial processes overcome those of the storm wave climate regime;
- a further analysis performed on South-oriented n-SDTs subset shows a clear logarithmic relationship between the local extreme significant wave height and ROD; the outcomes of this approach are promising so that future work will extend the numerical analysis here reported to a larger n-SDTs dataset.

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