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DOMENICO CAPOLONGO [1], EMANUELE GIACHETTA [1],
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GEOMORPHOLOGICAL NUMERICAL MODEL OF AN UPLIFTING COASTAL AREA: THE CASE STUDY OF TARANTO, ITALY

ABSTRACT: CAPOLONGO D., GIACHETTA E., ZINGARO M. & MASTRONUZZI G., *Geomorphological numerical model of an uplifting coastal area: The case study of Taranto, Italy.* (IT ISSN 0391-9838, 2022).

Marine terraces are usually indicated as subhorizontal surfaces cut by the action of the sea. Old marine terraces, standing above or below present sea level, can be covered by coeval sediments or not. The formation of marine terraces is controlled by the interplay between the vertical land movement and the sea-level oscillations. The correlation between sea-level curves and the current position of Quaternary marine terraces allows to define the local history of the uplift; this approach is frequently not accurate due to the subaerial erosion events experienced by raised marine terrace since the time of their formation. A 1-D numerical model was developed to help the interpretation and analysis of the evolution of a flight of Quaternary marine terraces in southern Italy during the last 430 ka We used SIGNUM (Simple Integrated Geomorphological NUmerical Model) landscape evolution model to simulate the 3D evolution of a topographic surface and to predict the geomorphic response of a coastal landscape to the reconstructed sea-level history, uplift rate and erosion processes. We applied the model in a coastal area of south-eastern Italy, near the city of Taranto; in this area one of the most studied successions of Pleistocene marine terraces of the Mediterranean area is located; here the most reliable data set of marine deposits is available, whose age was attributed to the MIS 5e. The modeling results were used to infer new hypotheses for the uplift and erosion history of the real landscape and as a basis for the development of general models of coastal landscape evolution under the forcing of sea level oscillations. We show that using the parameters that describe the different processes it was possible to reconstruct the sequence of marine terraces and to identify hypothetic polyphasic erosional surfaces.

KEY WORDS: Marine terraces, Coastal evolution, Sea-level change, Landscape evolution model.

RIASSUNTO: CAPOLONGO D., GIACHETTA E., ZINGARO M. & MASTRONUZZI G., *Modello numerico geomorfologico di un'area costiera in sollevamento: il caso di studio di Taranto, Italia.* (IT ISSN 0391-9838, 2022).

I terrazzi marini sono solitamente indicati come superfici suborizzontali modellate dall'azione del mare. Antichi terrazzi marini, al di sopra o al di sotto dell'attuale livello del mare, possono essere ricoperti da sedimenti coevi o meno. La formazione dei terrazzi marini è controllata dall'interazione tra i movimenti verticali del substrato locale e le oscillazioni del livello del mare. La correlazione tra le curve del livello del mare e l'attuale quota dei terrazzi marini consente di definire la storia locale dei movimenti verticali nel Quaternario; questo approccio spesso non è accurato a causa degli eventi di erosione subaerea subiti dai terrazzi marini rialzati sin dal momento della loro formazione oltre che per la ricorrente impossibilità di datare terrazzi di età maggiore ai 125 ka. È stato sviluppato un modello numerico 1-D per aiutare l'interpretazione e l'analisi dell'evoluzione durante gli ultimi 430 ka di una successione di terrazzi marini in Italia meridionale presso la città di Taranto. È stato applicato un modello di evoluzione del paesaggio SIGNUM (*Simple Integrated Geomorphological NUmerical Model*) per simulare l'evoluzione 3D di una superficie topografica e prevedere la risposta morfodinamica di un paesaggio costiero alle variazioni del livello del mare, al tasso di sollevamento e ai processi di erosione. Nell'area di Taranto si trova una delle più studiate successioni di terrazzi marini pleistocenici dell'area mediterranea; qui è disponibile il data set più attendibile del deposito marino più basso in quota, la cui età è stata attribuita al MIS 5e. I risultati della modellazione sono stati usati per inferire nuove ipotesi per la storia del sollevamento e dell'erosione del paesaggio reale e come base per lo sviluppo di modelli generali dell'evoluzione del paesaggio costiero sotto la forzante delle oscillazioni del livello del mare. Applicando il modello e i parametri che descrivono i diversi processi è stato possibile ricostruire la sequenza dei terrazzi marini e identificare ipotetiche superfici erosive polifasiche.

TERMINI CHIAVE: Terrazzi marini, Evoluzione costiera, Variazioni del livello del mare, Modello di evoluzione del paesaggio.

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INTRODUCTION

Whatever the origin of the uplift of a landscape (tectonic, hydro-, sedimentary-, volcanic-, glacio-isostatic), its interaction with the eustatic sea level change implies that several coastal areas of the world are marked by the presence of a staircase of quasi-flat surfaces corresponding to marine terraces (i.e.: Pirazzoli, 1996; Caputo & *alii* 2010; Mastronuzzi & *alii*, 2011). These surfaces are usually of Pleistocene age, rarely older as those observed in Eastern United States and southern Australia, where presumable Pliocene shorelines have also been recognised (Cronin & *alii*, 1984; Rovere & *alii*, 2014). The well-known, didactic sequence of the uplifted marine terraces of Turakirae Head, New Zealand, is only one example among many others studied in different areas of the world and in different geodynamics settings, either on active or passive continental margins (fig. 1). In general, the most spectacular examples of marine terraces, characterised by a great number of large surfaces and paleocliffs are recognisable in the areas where the uplift rates are higher (Pedoja & *alii*, 2011). Conversely, few data are known with respect to the distribution of terraced surfaces below the sea level.

Marine terraces are subhorizontal surfaces recognisable above or below the level of present wave action, regardless of whether these surfaces are covered (depositional) or not (abrasive) by sediments that are usually considered coeval with the underlying surface. Their age corresponds to a period when the interactions between the vertical land movement (VLM) and the change in sea level allowed to carve a flat surface. The hypothesis on the formation of staircases of marine flat surfaces was attributed by postulating that the main effect of temporary sea level stands is the cutting of flat surfaces following the rising lands (Pirazzoli, 1996), while in the case of a tectonically stable or subsiding coast, these erosional surfaces overlap or even cancel each other (Mastronuzzi & *alii*, 2011).

Few considerations have been made so far in order to compare the effects produced by the velocity of the sea-level oscillations relative to the uplift rates. A first attempt to model these phenomena was proposed by Cinque & *alii* (1995), followed by the computational model of the generation and degradation of marine terraces by Anderson & *alii* (1999). More recently, Trenhaile (2014) proposed a model that simulates terrace formation over a time period of about 5.5 ka. Usually, where well dated and correlated marine deposits are available, staircases of marine terraces have been used to evaluate the sequence of the sea level stands and the regional uplift (Brückner, 1980; Muhs & *alii*, 1990; Zazo & *alii*, 2003; Zander & *alii*, 2006; Caputo & *alii*, 2010; Saillard & *alii*, 2011). Stratigraphic and chronological data often proved inadequate to completely unravel the complex history of sea-level fluctuations, especially where erosion pre-

FIG. 1 - Sequence of uplifted marine terraces in different tectonic and isostatic contexts: A -San Clemente Island, California (Photo: D.Muhs, USGS; http://www.usgs.gov/climate_landuse/clu_rd/pt_sealevel_rise.asp); B - Bonaire, Netherland Antille (Photo: G. Mastronuzzi 11.3.2006); C - Tropea, Calabria, Italy (Photo: G. Mastronuzzi 4.8.2012); D - Langerstone Point, Prawle, Devon, UK (Photo: T. Atkin, licensed under CC-BY-SA-2.0. From Wikimedia Commons); E - Varanger Peninsula, Norway. The higher surface is at about 100 m (httpbrian-mountainman.blogspot.it2013_10_01_archive.html-Varanger). F - Turakirae Head, New Zeland (image from Google Earth).

vailed on deposition and in coastal areas characterized by low uplift rates (< 1 mm/y). In fact, the correlation between sea-level curves and marine terraces heights used to infer uplift rates is frequently not accurate due to the erosion history to which every raised marine terrace has been subject (Caputo, 2007). Uncertainties often arise in identifying past sea levels when this is based on the elevation of the inner margin of marine terraces or on the supposed location of shorelines inferred from the facies of the marine deposits. Erosion or sedimentation of a newly cut terrace surface can occur during subsequent sea level fluctuations; pedogenesis, obliteration by weathering and mass movements along the paleo cliffs, river incision, and differential tectonic uplift can alter or completely erase the original sequence of marine terraces, inducing errors in ordering the number of present marine surfaces. As a consequence, knowing the age of the lowermost deposit can be not sufficient to infer the age of higher surfaces and vice versa (Caputo 2007).

We developed a numerical model with the aim of helping interpretation and analysis of marine terraces in southern Italy, and to test the morphogenic response of a coastal landscape to the reconstructed sea-level history and to the first order erosion processes.

In the present work we simulated the formation and erosion of marine terraces using SIGNUM (Simple Integrated Geomorphological NUmerical Model), a Matlab, TIN (Triangulated Irregular Network)-based landscape evolution model (Capolongo & *alii*, 2011; Refice & *alii*, 2012; Giachetta & *alii*, 2014). We applied the model to a coastal area of south-eastern Italy, near the city of Taranto, where one of the most studied successions of Pleistocene marine terraces of the Mediterranean area is located; their age was attributed to the MIS 5e by dating the most reliable succession of the outcropping marine (i.e. Mastronuzzi & Sansò, 2003; Amorosi & *alii*, 2014 and references therein). SIGNUM model reproduces the time evolution of the topography through the interaction of four classes of surface processes: 1) diffusive erosion; 2) incision into bedrock due to channelized flow; 3) vertical land movements and 4) marine erosion (sea-bed erosion and cliff retreat). In this study we tested the parameters describing the modeled processes and integrated available data of marine processes (e.g. sea-bed erosion rate, depth of wave base, cliff retreat rate, initial slope of the coast profile) in the numerical model. Using the most suitable sea level curve and assuming a constant long-term uplift rate, we compared the modeled coast profile with the elevation profile extracted from the digital elevation model of the study area. We also show that using this numerical approach allows to reconstruct the sequence of marine terraces and to recognize non coeval erosional surfaces. The modelling results were used to infer new hypotheses for the uplift and erosion history of the real landscape and as a basis for the development of general models of coastal landscape evolution under the forcing of sea-level oscillations.

GEOLOGICAL AND GEOMORPHOLOGICAL DATA

The coastal area of Taranto lies between the Apulia carbonate platform to the East, representing a part of the Adriatic foreland, and the Bradanic foredeep to the West at the border of the Apennine mountain front (fig. 2). The area is characterized by the outcrops of the Plio-Pleistocene marine deposits consisting of nearshore calcarenite (Calcarenite di

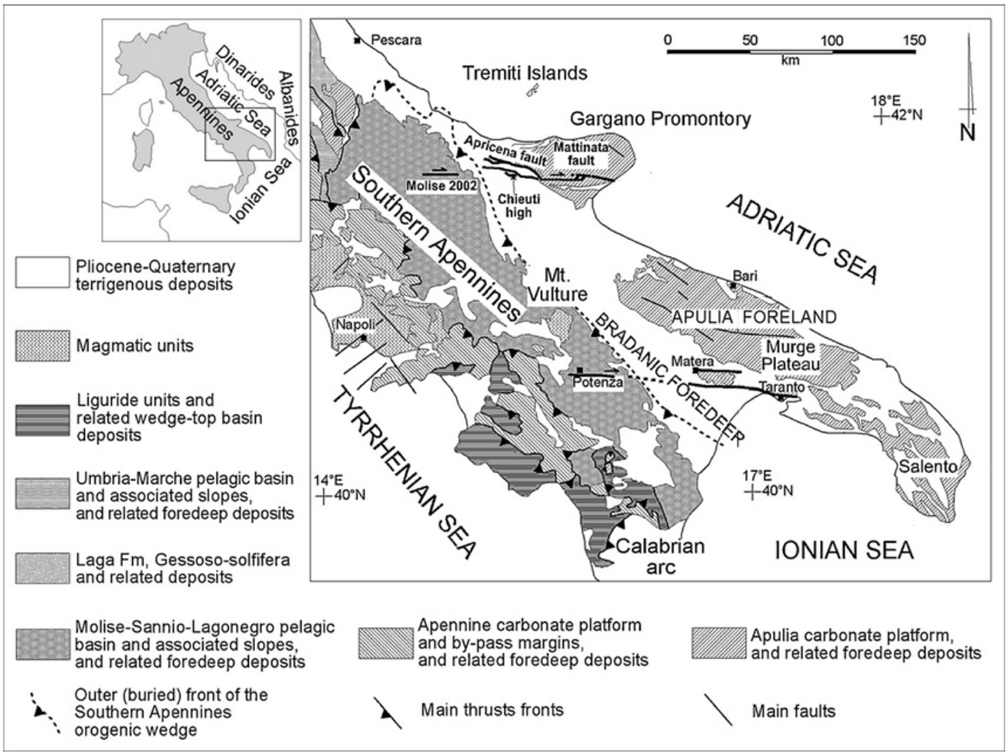

FIG. 2 - Geological and geodynamic context of the Taranto area (mod. from Di Bucci & *alii*, 2011).

Gravina Formation, sensu Tropeano & *alii,* 2002), laterally eteropic to offshore blue clay (Argille subappennine Formation, sensu. Tropeano & *alii* 2002); these marine sediments unconformably overlay the limestone of the Apulia platform (i.e.: Mastronuzzi & Sansò, 2003; Amorosi & *alii*, 2014).

During the Quaternary Apulia was affected by mild brittle deformation with rare faults (Di Bucci & *alii*, 2011; Mastronuzzi & *alii*, 2011; De Santis & *alii*, 2023). The interplay between local uplift and glacio-eustatic sea-level oscillations shaped a well-preserved staircase of marine terraces distributed in elevation between about 400 m and the present sea level, shaped on both limestone and Plio-Quaternary marine deposits. The number of the marine terraces is still debated and ranges from 16 to 7, incised by several meters deep fluvial valleys (i.e.: Mastronuzzi & Sansò, 2003 and references therein) (fig. 3). Some marine terraces lying below present sea level have also been recognised by geophysical surveys and approximately ascribed to the Holocene transgression (Senatore & *alii*, 1980).

The whole area around Taranto (fig. 4) is characterized by a flat and prominent surface attributed to the formation of a marine terrace during the maximum transgression of the last interglacial. This surface corresponds to the lowermost and largest terrace that crown the Apulia carbonate platform. Here, it overlies the Argille subappennine Formation (blue clay, Tropeano & *alii*, 2002) and its age has been locally attributed to ~0.5 My based on fossil records (Amorosi & *alii*, 2014; Negri & *alii*, 2015). Towards NW this surface is observed at higher altitudes along the front of the Apennines; while towards SE it is located at the original eustatic elevation of 6-7 m (Ferranti & *alii*, 2006; Mastronuzzi & *alii*, 2007). The deposits of this marine terrace stretch between about 23 m, where the inner margin and the relative beach/dune sediments have been recognized, and about 7 m (fig. 5). Theyhave been attributed to the Last Interglacial Time (LIT) since the presence of warm-water "*Senegalaise*" fauna (Belluomini & *alii*, 2002; Peirano & *alii*, 2004, 2009 and references therein). The fossil content, along with an impressive set of relative (amino acid racemization) and radiometric (U/Th) datings, indicate a tropical environment during Late Pleistocene, between 132 and 116 ka (about 125 ka), corresponding to MIS 5e (i.e.: Mastronuzzi & Sansò, 2003; Antonioli & *alii*, 2009; Amorosi & *alii* 2014; Negri & *alii*, 2015).

Sea level curve

Eustatic sea-level curves are commonly used to investigate the role of tectonics in the landscape evolution of coastal regions (Caputo, 2007). Knowing the sea-level oscillations and correlating the height of the terrace inner margin or deposits, it is possible to quantify the local and regional uplift. However, this method is approximate and not without drawbacks. The first problem is related to the reliability of the terrace elevation from the present one of the inner margin or derived by the analysis of the *facies* of the marine deposits, both used to identify the old sea-level position. The second approximation is related to the availability of a detailed and accurate time vs. sea-level curve. In fact, eustatic sea-level curves are derived from the conversion of the O^{18}/O^{16} ratio in sediment or ice core samples from different places around the world in equivalent sea level; speleothems, coral, bioconcrections and other geomorphological data allow together to improve the reconstruction of the sea-level history during the last gacial-interglacial hemicycle. The most recent eustatic curves (i.e.: Waelbroeck & *alii*, 2002; Siddal & *alii*, 2003; Bintanja & *alii*, 2005) show some uncertainties in the past sea-level position. Nothwithstanding these uncertainties, it seems now universally recognized that the position of sea level at the MIS 5e was about 7.0 m above the present position. However, the debate about the real position of the sea level during MIS 5c or during MIS 5a is still open.

FIG. 3 - The Taranto flight of marine terraces looking seaward.

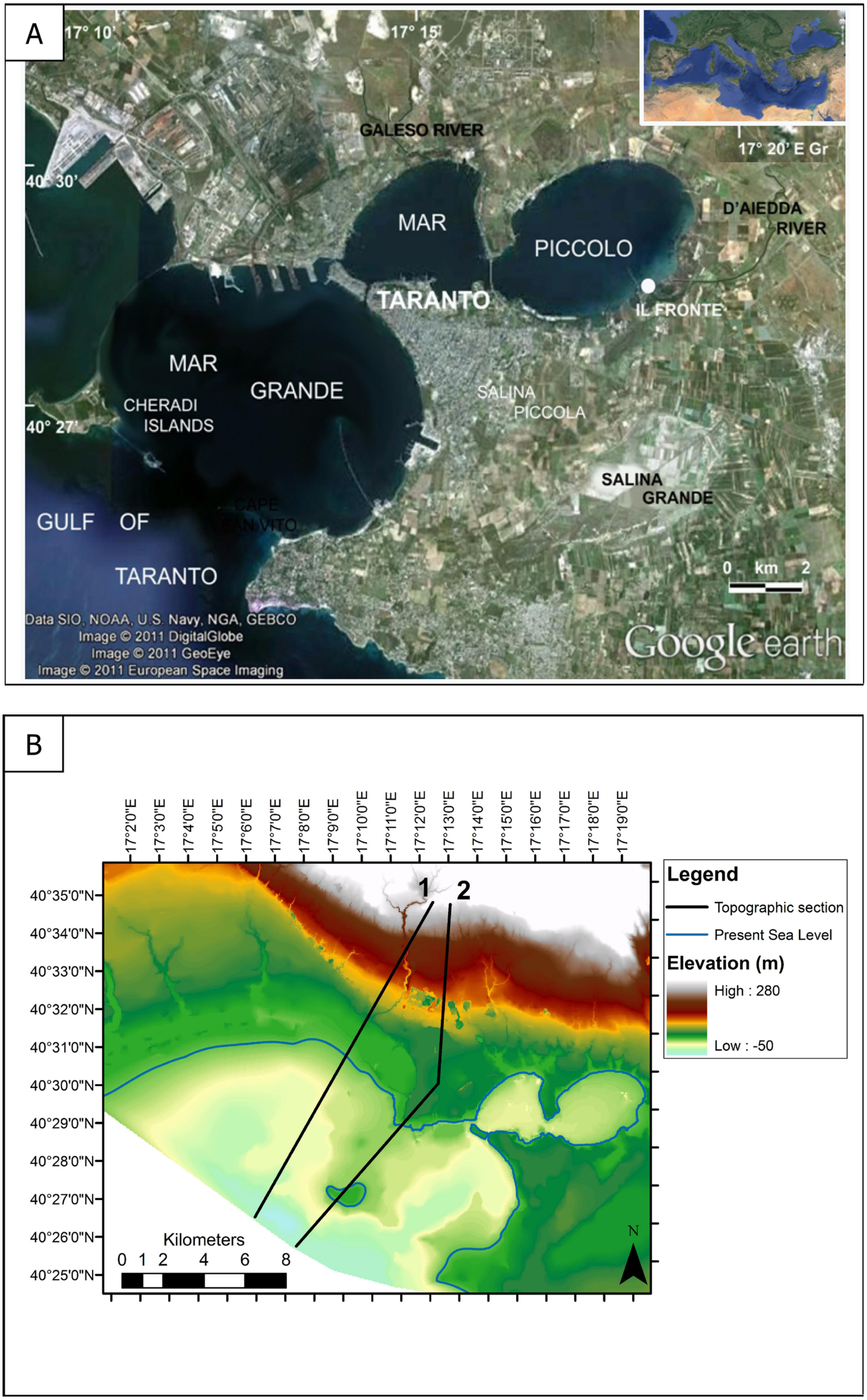

FIG. 4 - A: Geographical position of the study area. B: - The Digital Terrain Model reconstructed by means of photogrammetric techniques; the original horizontal resolution is 8 m. Traces correspond to the topographic profiles in fig. 14.

FIG. 5 - The flat surface present all around the Mar Piccolo and Mar Grande area: (a) - details of the inner edge north to the Mar Piccolo; (b) - the surface is evidenced by calcarenites overlapping the blue clay (Argille subappennine) of the local basement.

Uplift rate

Although the entire Apulia is considered a stable area, all along its coast a series of marine terraces has been detected, indicating at least a Plio-Quaternary uplift. In particular, it was evident that the presence of Thethystrombus latus (before *Persististrombus latus* and *Strombus bubonius*) correlated to the MIS 5e up to 20 m above the present sea level can be justified only considering the general raising of the area during the last 125 ka. In the study area, it is difficult to distinguish tectonic from isostatic uplift because both likely occurred at the same time; the total uplift rate was estimated by considering: a) the position of the inner margin of the large marine terrace that surrounds the city of Taranto corresponding to about 23 m above mean present sea level in a microtidal area (present tidal range does not exceeds the 0.5 m); and b) the original position of the sea level and of the shoreline that has been calculated to be about 7 m on the present one. On the other hand, there is no geological and geomorphological evidence to hypothesize that this uplift rates changed significantly during the considered time. As consequence it is reasonable to assume a mean value of 0.13 mm y^{-1} for this area (Ferranti & *alii*, 2006; Amorosi & *alii*, 2014).

Cliff retreat, sea-bed erosion and wave features

The recent *cliff retreat* rate in the area of Taranto can be derived by the availability of historical and archaeological data sets. The entire area around the Mar Piccolo and Mar Grande, the two inlets that limit the peninsula on which the settlement of Taranto was founded, is characterised by the presence of cliffs no more than about 15 m high and shaped on a sequence of blue clay at the base and calcarenite at the top. The coastal area retains a great deal of archaeological and historical information regarding the presence of human settlements as far as settlements of the Bronze age, aged to about 2.5 ka B.C., late-roman farms and villages aged to the VI-VIII centuries, and burials of Byzantine monks, partially collapsed during the retreat of the cliff (i.e.: Mastronuzzi & Marzo, 1999 and contribution therein). Even more precise details on the historical evolution of the coastline are found in the first cartographic representations of southern Italy by Italian and Saracen cartographers that show evidence of past collapses along the cliffs and indicate the depth of the seabed (fig. 6). Military and civil structures became more and more frequent over time along the coast of Taranto and the strategic location of the two inlets induced the cartographers to produce more accurate bathymetric and topographic maps of the area (Mastronuzzi & Marzo, 1999; Mastronuzzi & *alii*, 2006; 2013). Starting from the state of conservation of military structures and thanks to the comparison of the field surveys and the project of fortification of the bay, dating back to the XIX century, it has been possible to estimate a mean rate of cliffs retreat of the order of 0.8 mm y^{-1} (Mastronuzzi & Sansò, 1998, 2003).

Sea-bed erosion - The value of sea-bed erosion has been estimated from the comparison of different geographical maps produced by sailors, merchant and navies who attended over the time the larger bay, the Mar Grande (Mastronuzzi & Marzo, 1999). The oldest nautical maps dating back to the 16th century; they are descriptive and not constructed with geometric projections; for this only qualitative indications can be derived from them (fig. 6). Generally, the nautical charts from the 17th and 18th century have been built using nautical scales expressed in miles; they show depths in fathoms measured along detailed alignments that are considered also in nautical charts from the 19th century. Among these and up to those produced in the 20th century, the scale varies between 1/5000 up to 1/25000 and depths are expressed in meters. In the available cartographic documents a deep incision oriented about NNE-SSW is always represented; it corresponds to the main axis of the fluvial network that cut the area during the last glacial maximum (LGM) (Mastronuzzi & Sansò, 1998; Mastronuzzi, 2006; Valenzano & *alii*, 2018). In the coastal area, underwater morphology is represented by a flat surface extending from about 6.0 m of depth up to the coastline. This large surface corresponds to an erosive trasgression surface, shaped during the slowdown of the sea-level rise occurred from about 6.5 ka. The original erosive surface is currently discontinuously covered by the recent and present coarse sand in the shallow nearshore zone, and by silty-clay in the inlets. Based on these considerations, an average sea-bed erosion rate falling in the range 0.41-0.67 mm y^{-1} was used in the model.

Wave features - Starting from the data deriving from the RON (rete Ondametrica Nazionale managed by ISPRA - Istituto Superiore per la Protezione e la Ricerca Ambientale, www.ispra.it) it was possible to calculate the present depth of closure that is at about 6.5 m of depth. This value means that the present wave-cut platform (sensu Trenhaile, 1987; Sunamura, 1992) is still actively eroded by the wave action and that it is possible to identify an about 2 km wide wave-cut platform, although it is marked by the presence of significant thickness of finer sediments in the areas protected from sea-bed erosion.

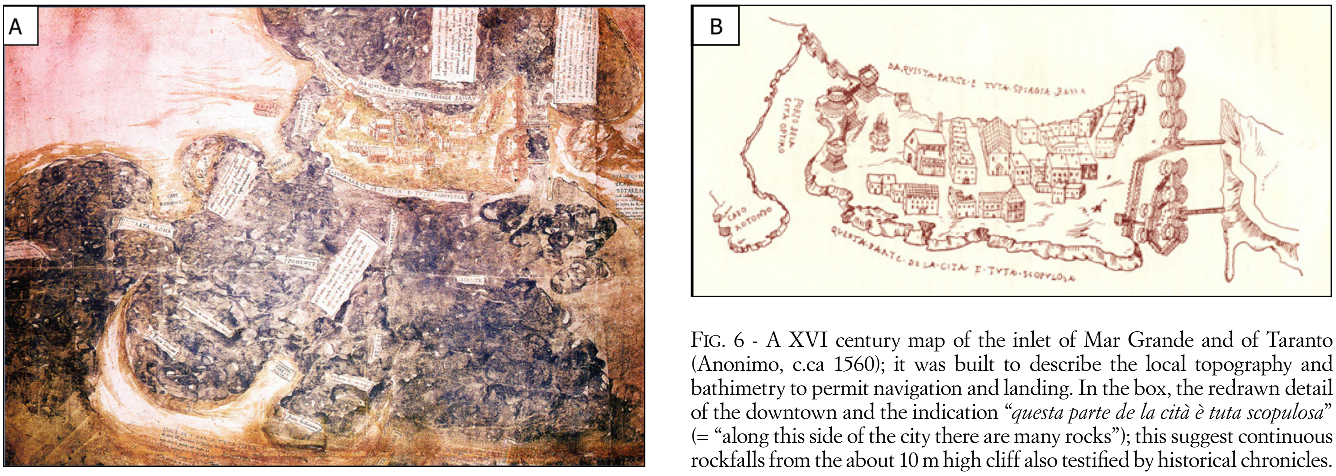

FIG. 6 - A XVI century map of the inlet of Mar Grande and of Taranto (Anonimo, c.ca 1560); it was built to describe the local topography and bathimetry to permit navigation and landing. In the box, the redrawn detail of the downtown and the indication "*questa parte de la cità è tuta scopulosa*" (= "along this side of the city there are many rocks"); this suggest continuous rockfalls from the about 10 m high cliff also testified by historical chronicles.

Channel and hillslope erosion

The marine terraces are dissected by straight and narrow bedrock valleys that represent a typical feature of the landscape (Donnaloia & *alii*, 2019). Each relict coastline is deeply modified in proximity of the outlet of these short valleys (Mastronuzzi & Sansò, 2002). The geometry and the general morphology of the stream network are mainly controlled by two bedrock lithologies: calcarenite and overconsolidated blue clay (see paragraph Methods). In the western part of the study area, where Plio-Pleistocene calcarenite is overlain by marine terraces deposits, channel incisions are deepened up to tens of meters in the surface of the terraces, and river profiles show in general high gradients. Mainly, these streams consist of a single channel confined by steep slopes, locally called "gravine" (Mastronuzzi & Sansò, 2002), with a length up to 10 km, a maximum width of 120 m and with a maximum incision depth of 50 m (for example the Gravina di Leucaspide River, fig. 7). The mouths of the longer and deeper valleys are located at the foot of the relict cliff that borders the marine terrace at about 55-60 m of altitude on the landward side. Both the main channels and their tributaries end abruptly upstream where a steep rock wall showing a "box-like" shaped headwater is observed.

The longitudinal stream profiles of the "gravine" show a general concave-up shape (fig. 8). The presence of several knickpoints separating channel portions with different concavities, are usually not lithologically controlled and indicate different waves of erosion migrating upstream due to base level change (Crosby & *alii*, 2007). These knickpoints correspond to waterfalls and related potholes.

On the eastern part of the study area, the fluvial network is characterised by bedrock channels and developed on overconsolidated blue clays. The drainage density is higher compared to the channel network developed on the calcarenites and the fluvial network has a dendritic configuration.

FIG. 7 - The landscape of the Taranto area is marked by bedrock valley locally called "gravine". They can be up to 50 m deep (Gravina di Leucaspide).

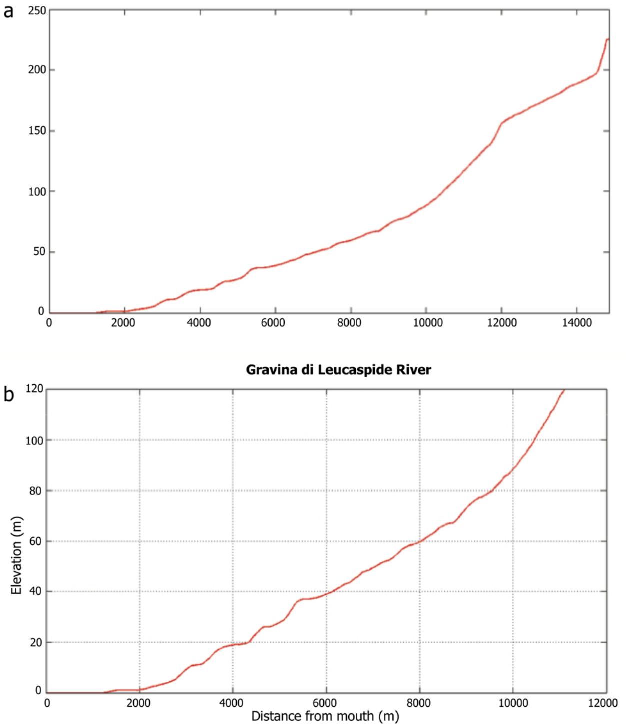

FIG. 8 - Gravina di Leucaspide stream long profile (a). Enlargement of the terminal onshore portion of the profile (b).

The hillslopes are typical of a low relief landscape and mantled by a thin soil cover. They are generally rounded shaped and convex, especially those developed on the overconsolidated blue clay due to the presence of a thicker weathered regolith layer at the top. Calcarenite is sometimes also covered by sandy-clayey deposits, produced by hillslope diffusion. Steeper hillslopes are observed along the flanks of the river valleys that carve the calcarenites and at the paleo cliff scarps. Rock falls and landslides affect these scarps.

METHODS

The numerical approach

We used a numerical landscape evolution model to give insights in the evolution of an uplifted coastal landscape and we compared the results with an 8 m resolution digital terrain model (DTM) obtained from aerial images. The model behavior is governed by a set of equations for tectonic displacement of the land, sea-level changes and erosion processes. The model is based on the principle of mass conservation, or continuity equation (Tucker & *alii*, 2001), which can be written as follows:

$$\frac{\partial z}{\partial t} = U - \nabla q_s \qquad \text{eq. 1}$$

where the left term is the change of elevation (z) through time (t) of a generic point of the topographic surface, U is the tectonic uplift rate and q_s is the sediment flux per unit width (∇ is the divergence operator). The second term on the right includes several processes, describing different erosion processes. Equation 1 states that in a unit volume the rate of change of elevation is equal to the difference between the mass entering into a given node and the mass exiting from the node. The form of equation (1) is independent of the time scale of the modeling, which means that Equation 1 can be applied either to long-term landscape evolution ($t > 10^4$ years) or to shorter time scales. To solve the mass-conservation equation (1), erosion and transport laws in numerical form are required for different geomorphological processes, as well as large-scale surface deformations (e.g. tectonic uplift and subsidence) and sea level changes must be represented in the numerical form. The numerical representation of each geomorphological process acting at the topographic surface are defined as geomorphic transport laws (hereafter, GTLs, Dietrich & *alii*, 2003).

A GTL describes the average mass flux on a definite spatial and temporal scale at a point on the landscape due to a particular geomorphic process. In general, a GTL represents a physically-based mathematical expression whose parameters can be estimated in the field. A GTL describes how the mean mass flux depends on topography, material properties, and other environmental factors (i.e. climate). When solved together with the continuity equation (1) given initial and boundary conditions and a function f(x, y, z, t) that describes the surface uplift, it provides a physical basis for predicting how the topography evolves. The solution of this equation is not straightforward and often needs numerical approaches. Among the most common GTLs are the ones used to model fluvial and hillslope processes, which represent the first-order processes controlling landscape erosion in continental environments. Some widely used expressions for river incision into bedrock and slope-dependent movements on hillslopes (e.g. linear diffusion) are reported in the following sections. These GTLs has been included as process modules in SIGNUM (fig. 9), and coupled with simulated surface uplift and eustatic sea-level change to solve the continuity equation they have been used in the experiments presented later.

SIGNUM is a multi-process numerical model used to simulate sediment transport and erosion at different space and time scales (Refice & *alii*, 2012). SIGNUM uses a triangulated irregular network TIN-based structure, which represents the topography by a set of points arbitrarily disposed on a surface. The main program deals with updating the model heights at each iteration, according to the chosen processes, whereas time is simulated as a sequence of discrete steps. At each iteration, height changes due to the selected processes are calculated at each time-step and then applied to all points of the TIN. This corresponds to a simple forward-in-time explicit resolution scheme, equal for all the equations pertaining to the various processes.

Modelling of geomorphic processes

In this section the equations controlling the landscape evolution of an uplifting coastal area are described. First-order processes such as 1) fluvial 2) hillslope erosion, and 3) coastal erosion were integrated in the numerical model. Fluvial erosion was proportional to unit stream-power along a channel and hillslope erosion was proportional to

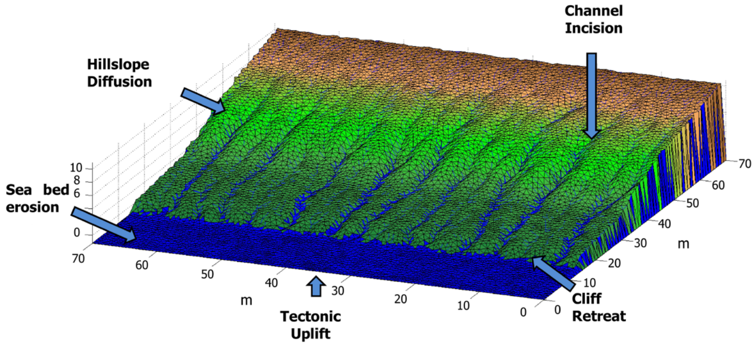

FIG. 9 - TIN-based synthetic topography and relative geomorphic process module in SIGNUM.

the topographic curvature. It was assumed that the amount of wave energy dissipated on the shelf was constant through time and produced a constant cliff retreat. In the model, we also assumed that all the debris produced by cliff retreat is easily comminuted and rapidly transported away from the base of the cliff. Despite these simplifications, the model allowed us to capture the essential aspects of the problem of modelling the marine-terraces generation.

Fluvial erosion was modelled in the form equivalent to the widely used "stream-power law" for fluvial incision (i.e. Howard, 1994; Howard, 1997; Stock & Montgomery, 1999; Whipple & Tucker, 1999). River incision was proportional to the water discharge at a point, Q, and local channel slope, S. Q is calculated by the formula $Q = A^{m}$, where A is the drainage area, used as proxy for discharge and m is typically 0.5 in the datachment-limited model (Whipple & Tucker, 2002). The stream-power model is commonly written in the form:

$$\frac{\partial z}{\partial t} = k_c A^{m} S^{n} \qquad \text{eq. 2}$$

where k_c is a constant including rock erodibility as well as other terms such as channel geometry, hydraulic roughness, and discharge regime (see Willgoose & *alii*, 1991), and m and n are positive constants that generally depend on the simulated erosion process. Equation 2 represents the detachment-limited model for river erosion in which deposition of sediment is neglected and all the amount of eroded material is assumed to exit the surface from one or more fluvial outlets. Commonly used values for m and n are around 0.5 and 1, respectively, although a range of values can be found in the literature, based on various assumptions about processes acting at thesurface and their characteristics (Gasparini & Brandon, 2011). However, many of such derivations maintain a value of the m/n ratio in a small interval around 0.5. The length scale of river erosion in the simulated landscape was short (maximum basin length ~10 km) and we assumed that transport capacity of rivers always exceeded the sediment supply in all simulations ("detachment-limited" regime; Howard, 1994).

Hillslope erosion was modelled as a diffusive process according to following equation:

$$\frac{\partial z}{\partial t} = kd\nabla^{2}z \qquad \text{eq. 3}$$

where k_d is the diffusion coefficient and $\nabla^{2}z$ is the surface curvature (Dietrich & *alii*, 1995, Roering & *alii*, 1999). The hillslope-diffusion function has been widely applied to the modeling of scarp degradation, including fault scarps and fluvial, marine, and lake-shore terraces (Tucker & Hancock 2010).

Coastal erosion was modelled assuming that sea-bed erosion and sea-cliff retreat act in response to local parameters (e.g. water depth) and eustatic and tectonic forcing. Following Anderson & *alii* (1999) and Snyder & *alii* (2002), sea-bed erosion over the marine platform was calculated using the following equation:

$$\frac{\partial z}{\partial t_{sb}} = \beta \left(\frac{\partial E}{\partial t}\right)_{0} \exp\left(\frac{-4h}{h_{wb}}\right) \qquad \text{eq. 4}$$

where β is a constant relating the erosion efficiency to the energy dissipation of waves, $(\partial E/\partial t)_0$ is the wave energy dissipation rate in very shallow water, h is local water depth, h_{wb} is the depth at which dissipation of waves is equal to zero. The value of β and $(\partial E/\partial t)_0$ are difficult to constrain, therefore we introduce a new parameter, k_{sb} encompassing these two unknown quantities (Anderson & *alii* 1999; Snyder & *alii*, 2002).

Therefore, after substituting k_{sb} the eq. 4 becomes:

$$\frac{\partial z}{\partial t_{sb}} = k_{sb}\exp\left(\frac{-4h}{h_{wb}}\right) \qquad \text{eq. 5}$$

Cliff erosion was modeled assuming that the wave energy available after dissipation in shallow water produced a constant cliff retreat rate.

Numerical simulation

The aim of the simulations was to gain first-order insights into the landscape response from the modeling of marine terraces generation and erosion in a coastal area incised by bedrock streams and affected by tectonic uplift and eustatic base-level changes. We performed coast profile (1D) and landscape (3D) numerical simulations.

In the modeling, the initial topographic profile perpendicular to the coastline was represented by a uniform slope of 1°, with a length of 15 km and a constant points spacing of 10 m. The simulation was started until reaching steady state coditions. The elevation of the modeled profile ranged between the present 150 m isobath and 150 m contour line, reproducing the area where calcarenite and blu clay outcrop. The 3D model surface had an average distance of 100 m between adjacent TIN's points, while the dimensions parallel (W) and perpendicular (L) to the coastline of the simulated area were 5 km and 15 km respectively. An uplift rate of 0.13 mm y^{-1} was kept constant and uniform in space and time. k_{sb} of equation (6) was set to 1 mm y^{-1} for all the experiments while h_{wb} was set to 7 m.

The values used for the model parameters imply that seabed erosion along the wave path was equal to zero at a water depth greater than h_{wb}, while it exponentially increased when the waves approach the coastline. Sea-bed erosion reached a maximum value (1 mm y^{-1}) in very shallow water while its average erosion rate was 0.65 mm y^{-1}. A sea cliff retreat rate of 0.8 mm y^{-1} was used in the modeling. The time vs. sea-level curve was calculated from the global sea-level oscillation curve obtained by Waelbroeck & *alii* (2002) for the last 430 ky (fig. 10). The river profile modeling was performed setting $m = 0.5$ and $n = 1$ in the stream power law of equation (2) (i.e. Tucker & Whipple, 2002), while k_c was varied in the range 10^{-3}-10^{-6} y^{-1}. The local drainage area A_i was calculated for each point of the profile as a function of the distance from the divide using the Hack's law (1957):

$$A_i = \frac{1}{4} * L_i^{1.67} \qquad \text{eq. 6}$$

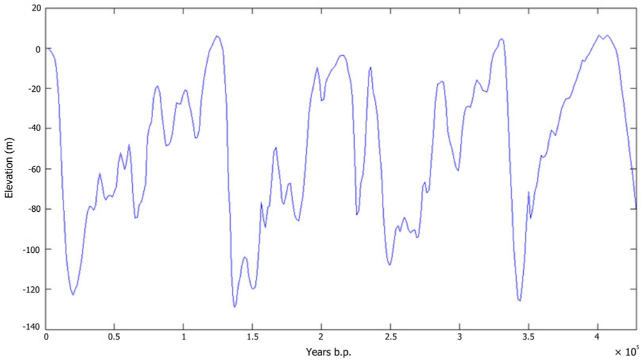

FIG. 10 - The curve proposed by Waelbroeck & *alii*, (2002) and used in the simulations; in the figure it is reported without the confidential interval.

The value of the hillslope diffusion (k_d) was set to 10^{-3} $m^2 y^{-1}$, considering this value as the average between those found in literature for umid and extremely arid climates (e.g. Tucker & Bras, 1998). Table 1 describes the model parameters used in the numerical experiments.

TABLE 1 - Model parameters.

Erodibility constant k_c (m^{1-2m} y^{-1})	1×10^{-6}
Stream power law exponents, m, n	0.5, 1
Diffusive erosion constant, k_d (m^2 y^{-1})	1×10^{-3}
Sea-bed erosion rate in very shallow water k_{sb} (m y^{-1})	1×10^{-3}
Depth of wave base h_{wb} (m)	-7
Cliff retreat rate k_{cliff} (m y^{-1})	0.8
Uplift rate U (m y^{-1})	1.3×10^{-4}
Initial slope S_{WCP}	1°
Length of 1D profile and 3D synthetic domain, L (km)	15
Width of 3D synthetic domain, W (km)	5
Simulation time t (ky)	430

RESULTS AND DISCUSSION

The erosive surfaces shaped by the waves of oscillating sea level, called wave-cut platforms (WCPS) and the cliffs modeled along a profile normal to the shore line after 430 ky are shown in fig. 11. The rate of sea level change derived from the sea-level curve by Waelbroeck & *alii* (2002) is shown in fig. 12. Modeled WCPS occurred in the modeled profile when the rate of the sea-level oscillation was less than the maximum sea-bed erosion rate and also when sea-level movements had the same velocity and direction of land movement.

The time sequence of forming WCPs can be observed in detail in a movie of the simulated profile provided in the supplementary material. The model predicts a final profile with 11 different WCPS shaped above and below present sea level (fig. 13).

The highest of these WCPS is found at an elevation of 50-60 m a.s.l.; it was shaped during the first sea level eustatic high-stand (between 410 and 390 ka) and is correlated to a cliff of about 15 m standing above this platform between 60 and 70 m a.s.l. In the time period between 390 and 345 ka, six different WCPs were shaped along the profile; these WCPS were subsequently reshaped by the following sea level rises. The inner edge of a large WCP is observed at ~42 m a.s.l.: it was shaped during the sea level drop around ~330 ka when the rates of sea-bed erosion and sea-level drop were almost equal; then the corresponding platform was eroded and shortened during following phases of sea level rise occurred between 330 and 270 ka.

In the following period of simulation, a 20 m high cliff was eroded during seven different events of WCP shaping that occurred at the present relative elevation ranging between 15 and 25 m a.s.l. and corresponding to seven relative sea level stands: ~380 ka, ~315 ka, ~285 ka, ~235 ka, ~215 ka, ~200 ka and ~125 ka. Another WCP with a ~6 m high cliff developed during the last ~7 ka of simulation, corresponding to the last phase of the Holocene sea-level rise. the WCPS recognised below the present sea level are eigth and were shaped in the model during the regressive phases and then partly eroded during their submersion. The platform generated at about -120 m corresponds to the last glacial maximum.

Fig. 14 shows the topographic profiles extracted from the 8 m DTM of the area and helps to compare the real topography to the result of 1D and 3D experiments. Profiles 1 and 2 show a ~20 m high paleo-cliff between 20 and 50 m above present sea-level, which is similar to the one generated in the model. These profiles show another WCP at an elevation between 50-60 m a.s.l., which probably correspond to the event simulated in the model around 410-390 ka. Remnants of other platforms are observed in the two topographic profiles between 15 and 25 m a.s.l.: these remnants could be related to seven events of WCPS generation simulated by the model in the same range of elevation. The wide platform and a ~6 m high cliff at the present sea level is also a common feature observed in the profiles from the DTM and in the real landscape.

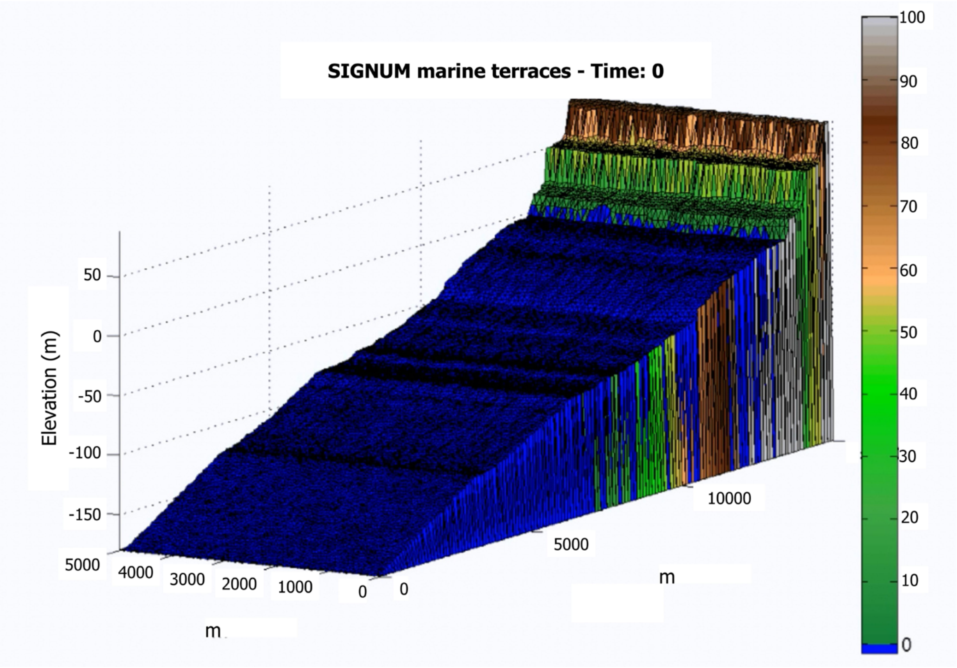

FIG. 11 - The 3D view of the final state of SIGNUM simulation; see the complete simulation video in supplementary data to have the 3D view of every year (cycle) along the last 430 ka.

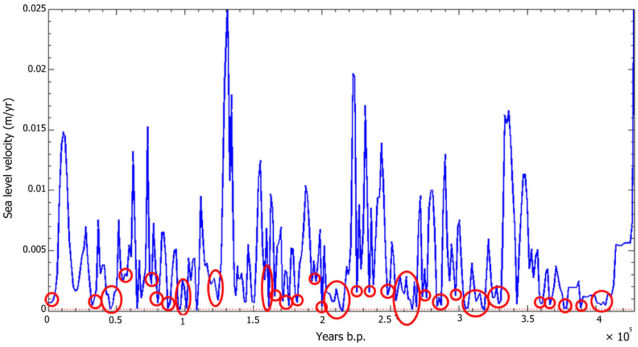

FIG. 12 - Rates of sea level change calculated from the global curve proposed by Waelbroeck & *alii* (2002); circles indicate the position in which sea level change permit the shaping of a wave-cut platform, assuming similar tectonic rates.

We also modeled the longitudinal river profile resulting from channel erosion and base level change. Fig. 15a shows the modeled profile using $k_c = 10^{-6}$ y^{-1}, resulting after 430 ky and the onshore portion of the terraces profile shown in fig. 15b. Knickpoints are formed by sea-bed erosion acting at the intersection between the river profile and the temporary stand of the sea-level. We calculated the difference between the points on the modeled terrace profile and those on the river profile obtaining an average incision of about 16 m.

We extracted a real river profile (i.e. the Gravina di Leucaspide River, fig. 8) from the 8 m DTM using the stream profiler tool (see Wobus & *alii*, 2006). Six knickpoints are observed in the channel profile of the Gravina di Leucaspide River at the elevation of 1, 10, 25, 35, 47, and 69 m a.s.l. The simulated profile also predicted the formation of knickpoints at similar elevations related to different base-level change that triggers waves of erosion migrating upstream through time. The depth of the incision along the valley of Gravina di Leucaspide River is also similar to the one predicted by the model (fig. 15b), suggesting a presumable $k_c = 10^{-6}$ y^{-1} for the outcropping lithology (calcarenite).

The 3D model results showed that rivers responded to changes in base-level and drove in turn the response of hillslopes enhancing the degradation of marine terraces. High values of bedrock erodibility decrease the time needed to dissect WCPS generated on the uplifting landmass. If erosion is sufficiently fast between two subsequent high stands, the relief of the slowly uplifting landmass can be dramatically reduced. Low-relief landscapes allow a deeper transgression of the sea at subsequent high stands. Depending on the bathymetry of the drowned low-relief landscape, sea-bed erosion can also contribute to level it. Successive cycles of transgression and regression and high subaerial erosion resulted in the generation of wider platforms. Figs. 16 and 17 show the different length of the resulting platforms using different values of k_c. The Higher is the modeled k_c, the shorter the WCP and vice versa.

In the study area, differences in width of the lower terraces are clearly related to the outcropping lithologies: the area of the Gulf of Taranto is mainly modeled in clays and the present and 125 ka WCPS are some kilometers wide. The geometry of the coastline and the presence of the gulf corresponds to the drowned drainage basin modeled on clays during the last 125 ka.

In the north-western part of the ionian coast and in the inner part of the Taranto gulf, marine terraces are modeled in limestones and calcarenites: the higher resistance of these lithologies together with high infiltration in karstified and fractured bedrock translates into lower discharge and stream power than rivers flowing on clays. This may have

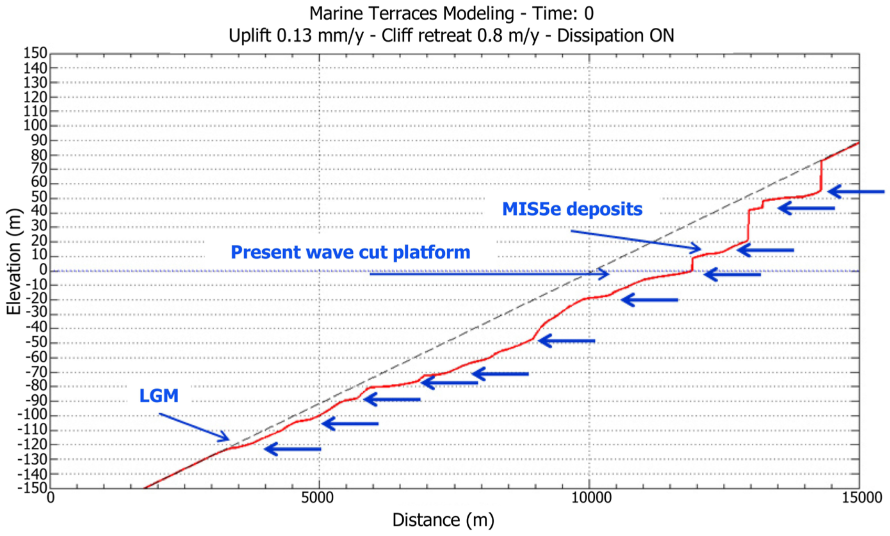

FIG. 13 - Result of SIGNUM model applied to the Taranto area for the last 430 ka. Eleven different wave-cut platforms are recognizable but some of them are poliphasic (see simulation video in supplementary data).

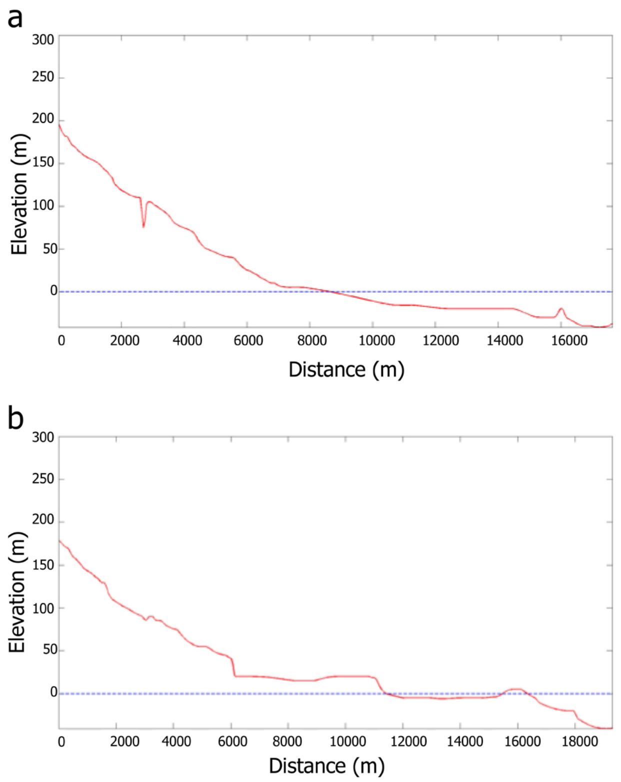

FIG. 14 - Topographic profile extracted from the 8 m DTM (fig. 4b) corresponding to the trace 1 (a) and 2 (b).

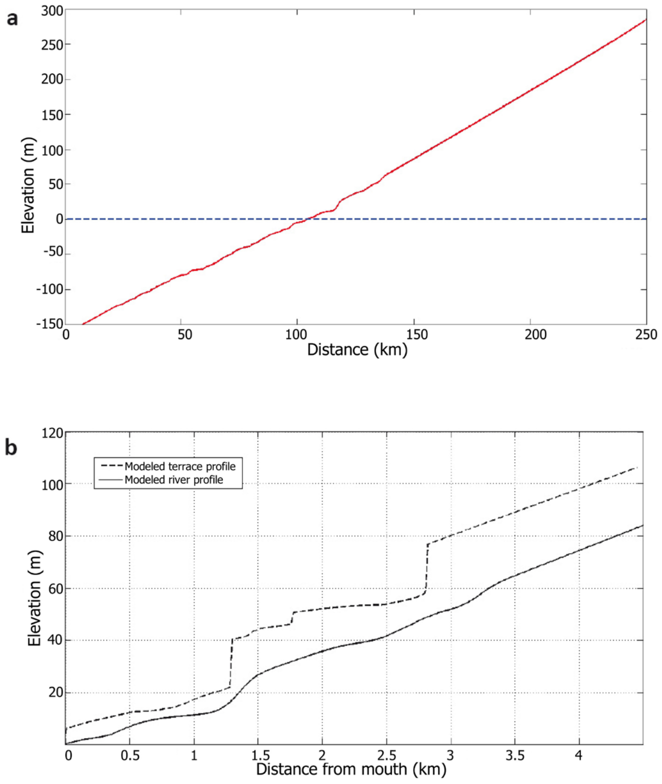

FIG. 15 - Result of modelling the interaction between stream incision and sea bed erosion after 430 ka (a) and onshore portion of the simulated terraces and river profiles (b).

helped to preserve the older WCPS for long time on limestones and calcarenites.

The thickness of sediments filling the paleochannels inferred from available geophysical data (Tropeano & *alii,* 2013) could provide some constraints on the magnitude of channel incision and subaerial erosion during the last cycle. Reconstruction of paleo-channel slopes and the horizontal distances travelled by older knickpoints can be used in the future to better calibrate the stream-power model parameters in the river profile modelling and to integrate them in new landscape evolution experiments.

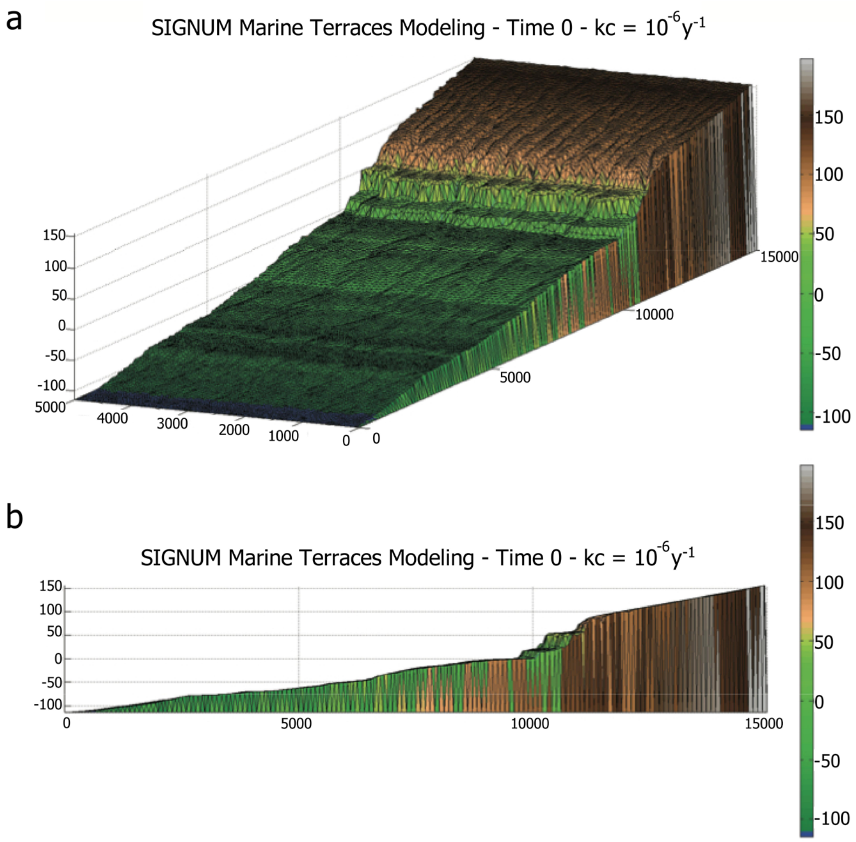

FIG. 16 - Perspective view of the landscape from modelling seabed erosion, cliff retreat, channeling using kc =1 × 10^{-6}, hillslope diffusion kd = 1 × 10^{-3}. (a) section view of the landscape shown above (b).

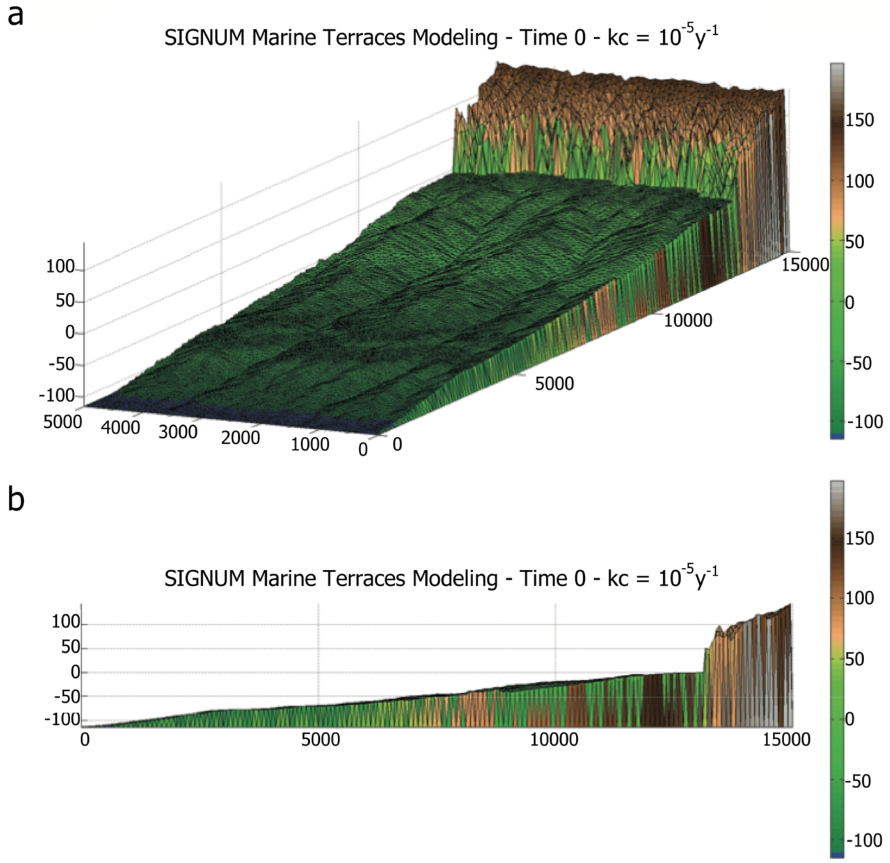

FIG. 17 - Perspective view of the landscape from modeling sea bed erosion, cliff retreat, channeling using kc = 1 × 10^{-5}, hillslope diffusion kd = 1 × 10^{-3}. (a) section view of the landscape shown above (b).

LIMITATIONS AND FUTURE DEVELOPMENTS

While the current landscape evolution model effectively simulates the formation and progression of marine terraces, it has inherent limitations that need addressing for enhanced precision and applicability. One primary constraint is the model's simplified representation of complex geological and climatic interactions, which may lead to inaccuracies when predicting terrace formations under dynamic environmental conditions. The model also assumes a uniform sea level change, overlooking potential local variations due to factors like tectonic activity or isostatic adjustment.

In the context of a landscape evolution model extended to a a long temporal scale of 500,000 years, the parameter estimation problem becomes exponentially complex and critically important. Currently, the model relies on parameters derived from present-day observations and near-term historical data, which may not accurately represent the geological and environmental processes occurring over past time periods. These parameters include, but are not limited to, rates of tectonic uplift, erosion and sedimentation processes, climate variability, and sea-level changes.

Solving the parameter estimation problem in this scenario will require a robust, multi-tiered approach. One strategy involves the integration of paleo-data reconstructions to inform parameter estimates based on evidence from similar geological epochs or analog environments. This would also necessitate the development of advanced statistical or machine learning algorithms capable of interpreting and learning from incomplete, and sometimes ambiguous, geological records. Another crucial aspect is the employment of uncertainty quantification techniques to assess the confidence and variability in the parameters chosen, acknowledging the unpredictability inherent in such long-term projections.

CONCLUSION

The proposed version of SIGNUM allowed improving our knowledge of WCPS generation and evolution in response to cyclic sea level changes and riverine/subaerial erosion. WCPS formed in the modeling when abrasion and sea-level oscillations had similar rate.

In the last 430 ka of simulated coastal evolution, forty-six events of terrace generation occurred producing only eleven WCPS. These platforms were distributed below (i.e. eight WCPS) and above (i.e. three WCPS) present sea level and the model reproduced a staircase of flat surfaces. The numerical simulations helped us to assess important constraints on the model for the landscape evolution of the study area. These are:

i - the higher WCP along the ionian coast formed by the older sea-level stands were partly eroded by following subaerial erosion;

ii - the immediately lower WCP is the relict of a larger one, a remnant of subsequent combined sea-level abrasion and continental erosion events;

iii - seven different relative sea-level stands – at 379-376, 330-324, 286-283, 238-236, 220-212, 197-196 and 132-116 ka – shaped on the blue clay and aged around 500 ka; the WCP at 15-25 m a.s.l. is covered only by sediment correlated to the last interglacial time (LIT) corresponding to the MIS 5e;

iv - since the LIT transgression, the wide marine terrace around the Taranto city was shaped on previous WCPS producing a polyphasic landform; the relative sea-level stand around 132-116 ka allowed the accumulation of the characteristic sediments with warm-water "*Senegalaise*" fauna;

v - WCPS below present sea level were partly smoothed as the result of sea-bed abrasion during regressive phases and were partly reworked during the subaerial erosion and succeeding sea-level rises; the attribution of these WCPS to the Holocene transgression must be confuted since sea-level rise during this period was so fast that could have not allowed to shape them;

vi - given the similarities between the modeled staircase of marine terraces and the profiles extracted from the DEM, a steady uplift rate of about 0.13 mm y^{-1} can be a probable condition for the last 430 ka as suggested by several authors (eg. Doglioni & *alii*, 1994, Schiattarella & *alii*, 2008) ;

vii - the present WCP has been shaped by the Holocene transgression from the flex-point of 6.5 ka in the sea-level curve;

viii - WCPS width depends on the outcropping lithology and the linear/areal subaerial erosion parameters;

ix - since the LIT transgression, the wide marine terrace around the Taranto city was shaped on previous WCPS producing a polyphasic landform; the relative sea-level stand around 132-116 ka allowed the accumulation of the characteristic sediments with warm-water "*Senegalaise*" fauna;

x - the profiles extracted from the 8 m DEM show a WCP at about 5 m a.s.l. that is not present in SIGNUM modeling; a possible explanation of this could be the original resolution of the DEM and a model limitation that is considering the average curve by Waelbroeck & *alii* (2002) and not its confidence interval.

SUPPLEMENTARY MATERIAL

Supplementary material associated with this article can be found in the online version, at http://gfdq.glaciologia.it/045_2_08_2022/ (SIGNUM 1D/3D simulation video)

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