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TIDAL NOTCHES (TN) ALONG THE WESTERN ADRIATIC COAST AS MARKERS OF COASTAL STABILITY DURING LATE HOLOCENE

ABSTRACT: FURLANI S., PIACENTINI D., TROIANI F., BIOLCHI S., ROCCHEGGIANI M., TAMBURINI A., TIRINCANTI E., VACCHER V., ANTONIOLI F., DEVOTO S., NESCI O. & MENICHETTI M., *Tidal notches (Tn) along the western adriatic coast as markers of coastal stability during late Holocene.* (IT ISSN 0391-9838, 2018).

In this paper, we present and discuss the spatial distribution of Tidal notches (Tn) along the western sector of Adriatic Sea as a marker of the coastal stability during late Holocene. Specifically, a 3.97 km long coastal reach at the Mt. Conero area has been investigated in relation to its geological and geomorphological pecularieties such as: i) active, low rates uplift; ii) active coastal plunging cliff; iii) diffuse gravity-induced instability of the rocky cliff and consequent presence of coastal landslides of different type, size and state of activity. The identification and location of Tn has been conducted on July 2016 by means of a snorkel survey along a route encompassing the toe of the Conero coastal cliff, allowing the investigation of the tidal zone and recognition of the morphotypes above and below the sea level. Time-lapse images with frame rate of 1 s were collected along the entire route. The best quality frames were used to precisely clusterize the coastal geomorphological features, and to precisely locate the recognized Tn. The snorkel survey was supported by detailed geomorphological surveys and geo-structural investigations from inland. This multifaceted approach allowed to identify and precisely locates Tn, other than to establish relationships among their morphometric features and other specific coastal morphotypes recognized in the field. Tn, here observed for the first time in the study area. Although the rocky coastal cliff is affected by active uplift and several active landslides of different types, sizes and depth, the Tn location and elevation suggests that i) late Holocene vertical deformations due to tectonic are negligible for the whole coastal sector analysed; ii) gravitaty-induced vertical deformations involving bedrock are negligible during at least the last couple of centuries in the coastal stretches where they are preserved.

KEY WORDS: coastal geomorphology, relative sea level change, gravitational mass movements, Mediterranean Sea.

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In questo articolo viene presentata e discussa la distribuzione spaziale dei solchi di marea (Tn) nell'Adriatico occidentale, come indicatori di stabilità costiera durante il tardo Olocene. In particolare, sono state rilevate 3.97 Km di coste rocciose nell'area del Monte Conero, in relazione alle loro peculiarità geologiche e geomorfologiche quali: i) basso ma attivo tasso di sollevamento; ii) coste rocciose verticali attive; iii) elevata instabilità delle coste rocciose a causa di movimenti gravitativi e conseguente presenza di frane costiere di diverso tipo, dimensione e stato di attività.

L'identificazione e la localizzazione dei Tn è stata effettuata nel luglio 2016 mediante rilevamento costiero a nuoto lungo il perimetro costiero del Monte Conero, permettendo la caratterizzazione della fascia tidali e il riconoscimento dei morfotipi costieri sopra e sotto il livello del mare. Durante tutto il percorso sono state raccolte immagini in time-lapse con frequenza di 1 s tra un fotogramma e l'altro. I fotogrammi più significativi sono stati usati per effettuare la clusterizzazione delle caratteristiche geomorfologiche costiere, e per localizzare i solchi di marea. Il rilevamento a nuoto è stato integrato da osservazioni geomorfologiche di dettaglio e rilievamento geostrutturale a terra. Questo approccio multidisciplinare ha permesso di identificare e localizzare con precisione i solchi di marea, oltre a stabilire una relazione tra le caratteritiche morfometriche dei solchi e altri specifici morfotipi costieri definiti su base fotogrammetrica.

In questo articolo i solchi di marea vengono descritti per la prima volta nell'area del Monte Conero. Sebbene le coste alte rocciose dell'area di studio siano soggette al sollevamento attivo e a differenti tipi di frana, la posizione e la quota dei Tn suggerisce che i) i movimenti tettonici verticali avvenute nel tardo Olocene sono trascurabili per l'intero settore

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costiero analizzato; ii) anche le deformazioni verticali indotte da movimenti gravitativi, che hanno interessato il substrato roccioso, sono trascurabili negli ultimi due secoli nei tratti di costa in cui sono conservate.

Termini chiave: Geomorfologia costiera, variazioni relative del livello del mare, movimenti di massa gravitazionali, Mar Mediterraneo.

INTRODUCTION

More than half of the Mediterranean Sea is bordered by rocky coasts, most of them interested by unstable sea cliffs due to mass movements, but only few sectors were surveyed and studied in detail (Furlani & *alii*, 2014a). Moreover, further researches are needed for improving present knowledge about rocky coastal mophodynamics, also in terms of hazard assessment within these areas that have strategic significance due to economic, social, environmental and cultural activities competing for vital space.

Notches develop as a result of higher erosion rates in the tidal zone rather than in the supratidal or subtidal zone (Furlani & *alii*, 2009; Furlani & Cucchi, 2013; Moses, 2013; Moses & *alii*, 2014). These type of notches are called Tn, or u-shaped, as suggested and described by Pirazzoli (1986), Carobene (2014) and Antonioli & *alii* (2015) in the central Mediterranean. Evelpidou & *alii* (2012) suggested the global disappearance of present-day Tn, later denied by Antonioli & *alii* (2015) showing more than 70 sites with actual Tn in the Mediterranean basin. Tn are widely used as sea level markers (e.g. Pirazzoli & *alii*, 1996; Benac & *alii* 2004, 2008; Faivre & *alii*, 2011; Antonioli & *alii* 2017). Wave abrasion plays little contribution in notch development in the Mediterreranean Sea (Antonioli & *alii*, 2015), unlike outside it (Trenhaile, 2015).

In rocky coastal areas, slope instability analyses require the understanding of the interactions between intrinsic rheologic and litho-structural characteristics of the cliffs and external stresses (Trenhaile 1987; Sunamura 1992; Dipova 2009, Bezerra & alii& *alii*, 2003, Pellicani & *alii*, 2015) such as wave motion and sea level changes. Changes in sea level occur over a wide range of spatial and temporal scales, with many contributing factors, at both global and local scale (Lambeck & *alii*, 2004). In the Mediterranean basin, relative sea level changes are the result of a complex interplay between tectonic, glacio-hydro-isostatic and eustatic processes (Lambeck & *alii*, 2004). Methods and markers to study the relative sea level changes in the Mediterranean were reviewed by several Authors (e.g. Anzidei & *alii*, 2014; Shennan & *alii*, 2015).

Coastal hillslope processes can be prone to evolve in paroxysmal events (Qin & *alii*, 2001; Blikra & *alii*, 2005; Bornhold & Thomson,2012) or display a continuous slow activity associated with creep evolution of rocky slopes (Chang & *alii*, 2015; Devoto & *alii*, 2013; Piacentini & *alii*, 2015; Mantovani & *alii*, 2016). Several studies have documented slope-failure distribution along the western Adriatic coast (Crescenti & *alii*,1986; Centamore & *alii*,1997; Crescenti & *alii*, 2003; Fiorillo, 2003; Iadanza & *alii*,2009) but only few works have evaluated the role of coastal erosion processes and the consequences of sea-level change as controlling factor for slope instability (Violante, 2009; Della Seta & *alii*, 2013).

An area particulary prone to landsliding owed to a high rocky coast overhanging directly to the sea (Montanari & *alii*, 2016; and references therein) and a high fracture density of the carbonate layers outcropping (Diaz-General & alii, 2015) is the Mt. Conero coastal zone. Here, the cliff retreat, that is the main surface process controlling the rocky coast morphoevolution, is mainly conditioned by litho-structural factors. In this area, one step of the Geoswim project has been conducted during the summer 2016 for completing the researches along the western coastline of the Adriatic Sea.

The Geoswim project started in 2012 with the aim of collecting continuous data, namely images and observational data, using a snorkelling approach, along all the rocky coasts of the Mediterranean basin (Furlani & *alii*, 2014a). The Geoswim method is particularly effective to study in detail kilometre-long sectors of coasts and to discover selected coastal features, such as Tn (Furlani & *alii*, 2014b, 2017), which are considered among the best present and past sea level markers because its close relation with processes acting in the tidal zone, such as waves, biological and chemical weathering (Antonioli & *alii*, 2015). The large database discussed by these authors is lacking of information in the Conero area. The survey carried out in this research allowed to finally fill this gap.

With these premises, detailed geomorphological and geo-structural surveys, above and at the sea level, were performed in order to identify and describe in detail geomorphic markers of sea level change, such as Tn, as well as to esthablish specific relationships with the slope instability of the rocky cliff, contributing to estimate the Late Holocene morphoevolution of Mt. Conero area (fig. 1). In particular, the characteristics of the present tidal notch, which have never been reported so far for the study area, and the results of a detailed image analysis of the geological and structural features surveyed will be presented and discussed.

STUDY AREA

The Conero promontory (latitude: 43°33'04" North, longitude: 13°36'18" Est) represents the inflection point of the Adriatic coast in the central Italy. The coastline here shifts from a NW-SE orientation, in the upper part, to a NNE-SSW orientation in the lower sector. (fig. 1). The surveyed sector comprises 4 km of coastline limited by the "Vela" seastack (North) and by the cliff called "Pirolo" (South) including the "Due Sorelle" seastacks. The altitude is ranging from present sea level up to 572 m a.s.l. in the Mt. Conero top, which constitutes the highest relief along the Adriatic coast. The cliff at Mt. Conero area is exposed to NE and E, with a shore platform gradient of few degrees until 1 km offshore to a maximum depth of 20 m.

The climate is warm-temperate of the Mediterranean type with mean annual precipitation of 780–790 mm and mean annual temperature of 14-15 °C. Summers are hot and relatively dry, whilst a pronounced variability mainly depending on the Atlantic cyclogenesis characterizes winters (Savelli & *alii*, 2017).

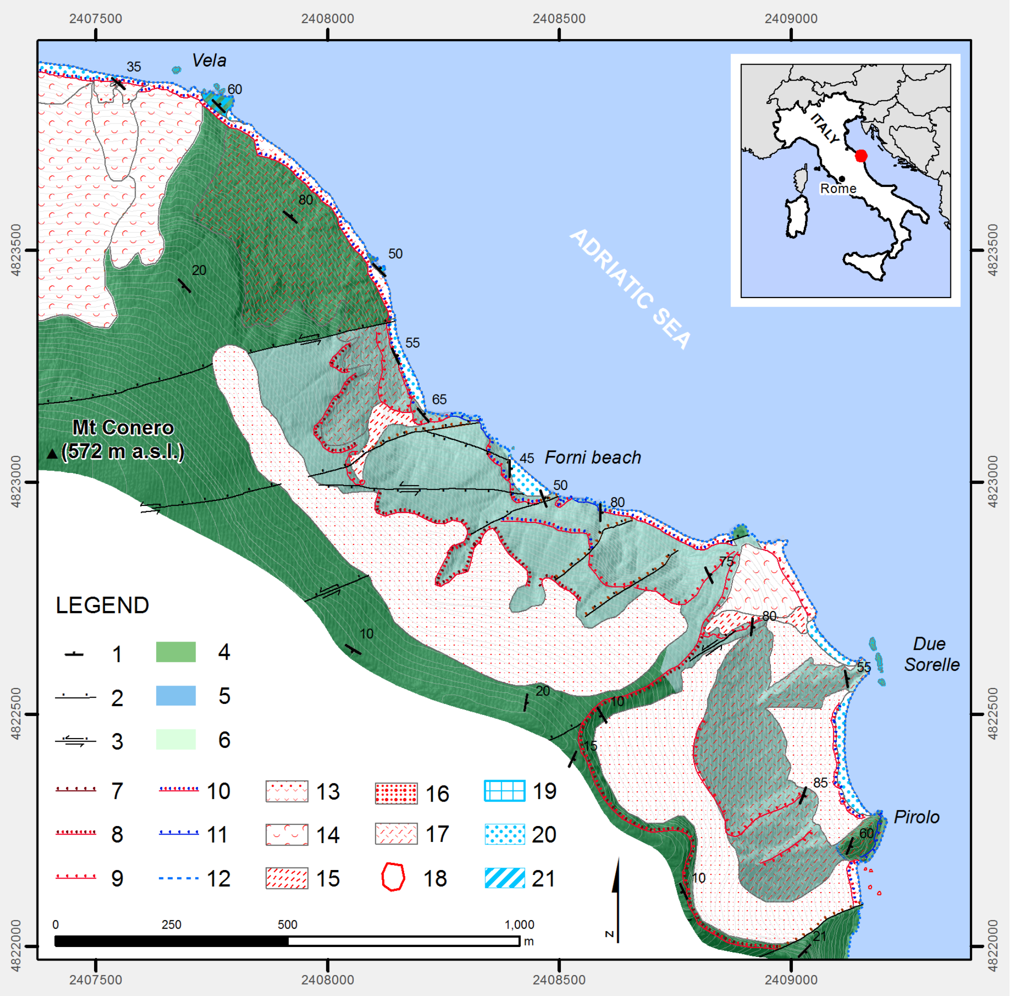


FIG. 1 - Geological and geomorphological framework of the Mt. Conero area. 1: Attitude of strata; 2: Fault; 3: Strike-slip fault; 4: Scaglia Bianca Fm.; 5: Marne a Fucoidi Fm.; 6: Maiolica Fm.; 7: Edge of structural scarp; 8: Edge of structural scarp remodeled by gravitaty-induced processes; 9: Edge of gravity-induced scarp; 10: Edge of gravity-induced scarp remodeled by marine processes; 11: Edge of coastal cliff; 12: Coastline; 13: Rockfall; 14: Rockslide; 15: Debris flow; 16: Talus slope deposits; 17: Diffuse rock slope instability; 18:Rock block; 19: Sea stack; 20: Beach; 21:Shore platform.

The coastal morphodynamics of the area are mainly driven by prevailing winds approaching from the sector SSE-SSW (Mastronuzzi & *alii*, 2017), that generate significant wave refraction affecting the high coast portions with SE main wave direction. Storm waves of up to 3-3.5 m can occur particularly in the winter months associated with Bora wind condition and with NE secondary wave direction. The bimodal wave direction strongly affected the high dynamism of the coastline the morphology beside that the grain-size variation and the consistent shoreline rotation of beaches (Harley et al., 2014; Grottoli et al., 2016). The average tidal range is about 0.5 m and the action of tidal current are extremely low.

The Mt. Conero is NE verging asymmetric east verging anticline with NNW-SSE axial directions (Cello & Coppola, 1984; Montanari & *alii*, 2016) that represent the easternmost outcropping part of the external stack of the Umbro-marchean foreland fold and thrust belt.

The bedrock of the coastal stretch investigated alternates prevalently limestones and marly-calcareous terrains belonging to the Umbria-Marche stratigraphic succession (Montanari & *alii*, 2016) from Createaceous to Oligocene in age.

This stratigraphic sequence is well-exposed at the Pirolo cliff, where the pelagic formations from the Upper Jurasic Maiolica up to Paleocene Scaglia Rossa crop out (fig. 1) along a seaward consequent slope of the external flank of the anticline. In the area, this stratigraphic sequence presents some peculiarities with respect to that outcropping in the internal area of the Apennine chain. In fact, the Marne a Fucoidi Fm. is about 3-5 m-thick, very thinner with respect to the regional typical thickness (about 80 m) and the Scaglia Bianca Fm, togheter with a part of the basal portion of the Scaglia Rossa Fm, are totally missing due to sysnsedimentary slumps. This is the most probably cause of the paraconformity erosive contact between Marne a Fucoidi and Scaglia Rossa formations (Crescenti, 1969; Coltorti & *alii*, 1987). The limestone bed thickness both in Maiolica and Scaglia vary from decimetre to a meter in the Upper Cretaceous calcarenite. In the upper part of the Maiolica and in corrisponcence of the Marne a Fucoidi, there are interbeds of clays and organic-rich marls. Limestone layers of the Scaglia Rossa Fm., separated from the mainland by a narrow stretch of water formed by the selective erosion on the less resistant Marne a Fucoidi Fm. (prevalently marls), made up the "Due Sorelle" seastacks (Montanari & *alii*, 2016).

The western side of the Mt. Conero anticline is gently dip (around 25°) and affected in the inner part by SW dipping normal faults. The eastern flank is strongly inclined (even 80° along the coast) and interested by several trasversal left-trastensive faults with an average E-W direction. In addition, there are few N-S right-lateral strike-slip faults. Metric shear zone is associated to these fault planes outcrop in different sectors of the structure and adjusting often offset of a few kilometers. The shear zones are characterized by cataclastic deformation, with calcite veins indicating the important role played by fluid flow (Diaz-General & *alii*, 2015).

Several seismic reflection profiles acquired for hydrocarbon industrial purpose, show that the Mt. Conero anticline overthrusts for few kilometres over the external offshore syncline along a high angle surface (Maesano & *alii*, 2013). The upper part of the thrusts staircase trajectory, splays into shallow minor structures where wrench and compressional structures involve Messinian and Plio-Pleistocene foredeep sediments. Towards the South, the anticline is affected by shallow low-angle crestal thrusts rooted in the Messinian and Plio-Pleistocene sediments. These compressional features involve the upper part of the Upper Pliocene and possibly the Quaternary stratigraphic sequence. The activity of the structures is well-documented by diffuse crustal seismicity from the Po valley to the Central sector of the Adriatic Sea. Historical seismicity shows that, at least in the upper crust, the compression is still active in different sectors of the compressive front. The whole geometry of the deep offshore structures is quite complex because the presence of interplay of back and fore-thrusts with overprinted by normal faults.

The joint pattern is well developed in the rock masses. A pervasive cleavage with subvertical SW dipping planes is observable expecially in the Maiolica and in calcareous Scaglia Rossa bedding. Subohorizontal diagentetic stylolites are quite common in the Maiolica Fm. Sub-vertical joints are developed expecialy in the Scaglia Rossa Fm., with systems striking NW-SE and ENE-WSW, associated with brecciate shear zones and systematic calcite viens.

Litho-structural factors, combined with gravitaty-induced and coastal processes, strictly controlled the morphodynamics and related morphotypes along the cliffs. The very high fracture density of the carbonate layers plays a fundamental role as predisposing factor of numerous landslides, triggered by severe rainfalls, earthquakes and marine action at the base of the cliff. Recurrent collapse events are mainly characterised by rockfalls, rockslides and debris falls (Fruzetti & *alii*, 2011; Aringoli & *alii*, 2014). Rockfalls are the most common phenomena, contributing to high erosion rates, which can reach several decimeters per year (Duperret, 2004; Mortimore, 2004; Lim & *alii*, 2009; Santos & *alii*, 2011; Barlow & *alii*, 2012; Katz & Mushkin, 2013; Martino & Mazzanti, 2014). Wide talus slope deposits occur as depositional result of the intense gravity-induced erosion in the upper zones of the cliff (fig. 1). Secondary landslides and the sea-waves action during storm events produced a well-evident, active wave-cut scarp at the base of the talus slope deposit. At the base of the cliff, small beaches appear, consisting in rocky blocks and gravels (Savelli & *alii*, 2017).

MATERIALS AND METHODS

This research was carried out using a multidisciplinary approach including geomorphological observations collected during a snorkel survey, integrated by inland geomorphological and geo-structural surveys.

Geomorphological surveys on the terrestrial sector focused on the recognition of landforms, mainly related to gravity-induced and coastal processes, with particular attention to the recognition of the geomorphic markers of past sea levels, useful for unravelling the morphoevolutionary context of the area in response to climate change and tectonics (Burbank & Andersson, 2011). The latter, in the slightly uplifting northern Marche coast, usually are remnants of late Quaternary coastal terraces, coastal fans at the main river mouths and relict wave-cut scarps (Troiani & Della Seta, 2011; Nesci & *alii*, 2012; Dall'Aglio & *alii*, 2017). The aim of such analyses was to provide preliminary constraints to the long-term morphoevolution of the coastal cliff, in particular for unravelling the complex causal interplay between sea-level variations and the instability of the coastal slopes.

In support, geo-structural surveys ware performed to detect and characterise the main structural features, which highly control the rock mass behaviour, and to unravel the connection between bedrock discontinuities frequency and distribution and slope instability. Thanks to the currently widespreads techniques of digital survey, structural data were directly collected in digital form allowing to set up a statistically significant database.

The snorkel survey was carried out along a route of 3.97 km, from the Pirolo cliff to the stack locally called "Vela" (fig. 1). The survey adopetd the protocol suggested by Furlani & *alii* (2014a, 2017). The survey was carried out using snorkel observations during the 18th of July 2016 at ~1 m from the shoreline, following northward the favourable wind driven currents. A specially designed raft, 1 m long, which was pushed or dragged, was used to house all the surveying equipment during the snorkeling activities. One GoPRO camera, located in a semi-submerged dome, allowed to collect time lapses of large part of the observed coast, both above and below the sea level. A CTD diver has been added to collect the temperature (T) and the electrical conductivity (EC) during the survey (fig. 2).

Coastal morphotypes were recognized and mapped following Furlani & *alii* (2014b) and Biolchi & *alii* (2016). The morphometric parameters of Tn were estimated following Carobene (1972), Furlani & *alii* (2011) and Antonioli & *alii* (2015) using a metric invar rod. Detailed morphometric parameters were measured taking into account the average notch width and depth, and the depth of the cliff toe (Antonioli & alii 2015). They represent a mean value of repeated measures with a small error bar (less than ±0.10 m). The measures of elevations were compared to the local tide using data provided by ISPRA at the tidal gauge of Ancona (Lat: 43°37'29.16", Long: 13°30'23.46", http://www.mareografico.it), but differences were lower than 0.05 m during the surveying time. Wind direction and velocity during the surveying period were collected at the same station.

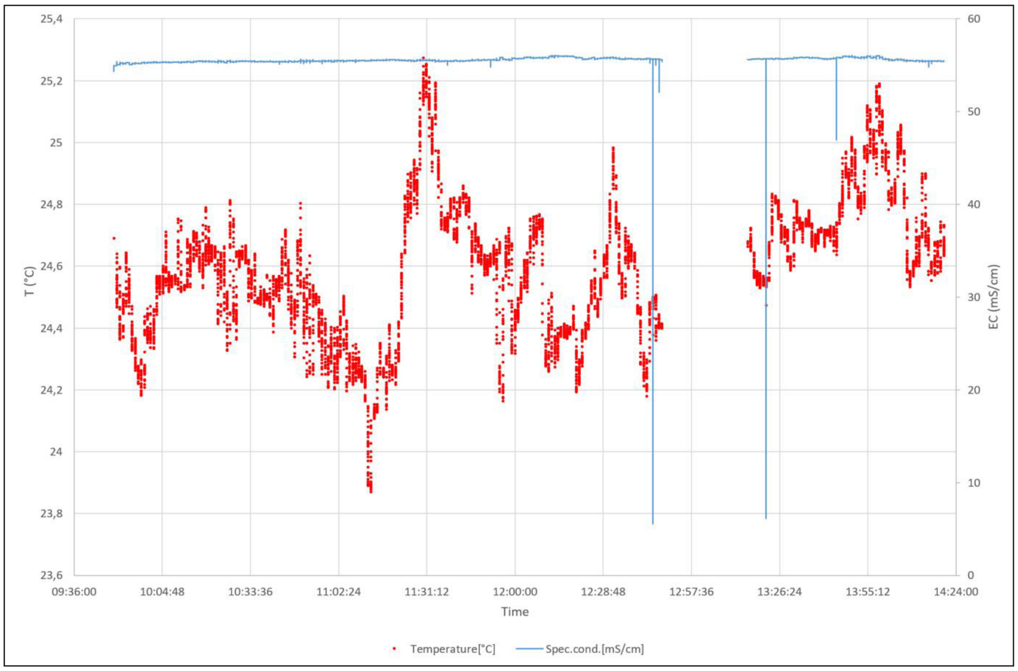


FIG. 2 - Temperature and conductivity during the survey time. The lower values of EC could be related to submarine springs.

Visual analysis of time-lapse images was performed to obtain the following parameters: 1) position of the image compared to the mean seal level; 2) distance from the coastline; 3) direction of acquisition (perpendicular or inclined) with respect to the coast; 4) relative turbidity from visual analysis; 5) inclination of the coast (high, medium, low); 6) presence of particular landforms such as Tn, stacks, abraded forms, joints, blocks, human-made structures and sea caves. The evaluation of the relative turbidity during the survey was also performed by analyzing the plot profile of the greyscale intensities of the submerged part of the image (fig. 3). The analysis was carried out on 50 random images, or 18.7% of the selected images. For every image, the histogram and the standard deviation values have been calculated.

Six coastal morphotypes have been used to classify the coastline depending on its topographical, structural and geomorphological characteristics (Furlani & *alii*, 2014a; Biolchi *& alii*, 2016): *plunging cliff*, defined as vertical or sub-vertical cliff descending into a considerable depth far below low-tide level and without any development of shore platform or ramp. The slope is >45°; *sloping coast*, which are low-lying rocky coast with slope dips ranging between 5° and 45°; *shore platform*, defined as horizontal/sub-horizontal rock surface (0-5°) induced by bedrock lowering in the intertidal zone; *screes*, which are the results of extensive landslides, *cliffs*, which are vertical steep slopes front to the sea; *pocket beach*, which are sand, gravel or pebble deposits within bays and inlets.

Digital elevation data derived from topographic maps, available in digital vector format 1:2000 and 1:5000 scales, were used to obtain a 5x5 m gridded Digital Elevation Model (DEM) of the subaerial portion of the Mt Conero area. The 2x2 m gridded DEM available in the framework of the Project PST-A (Piano Straordinario di Telerilevamento - Not Ordinary Plan of Remote Sensing, Ministero dell'Ambiente e della Tutela del Territorio e del Mare), multitemporal orthophotos and DEM-derivered hillshade maps were also were also used for assisting the inland geomorphological surveys.

RESULTS

Physical conditions during the snorkel survey

The sea temperature was comprised between 23.87 °C and 26.22 °C, while the average termperature was 24,59 °C. The electrical conductivity (EC) was comprised between 5.54 mS/m and 56.07 mS/m, with an average value of 55.55 mS/m. Lower values of EC can be tentatively related to the presence of two submarine springs (fig. 2).

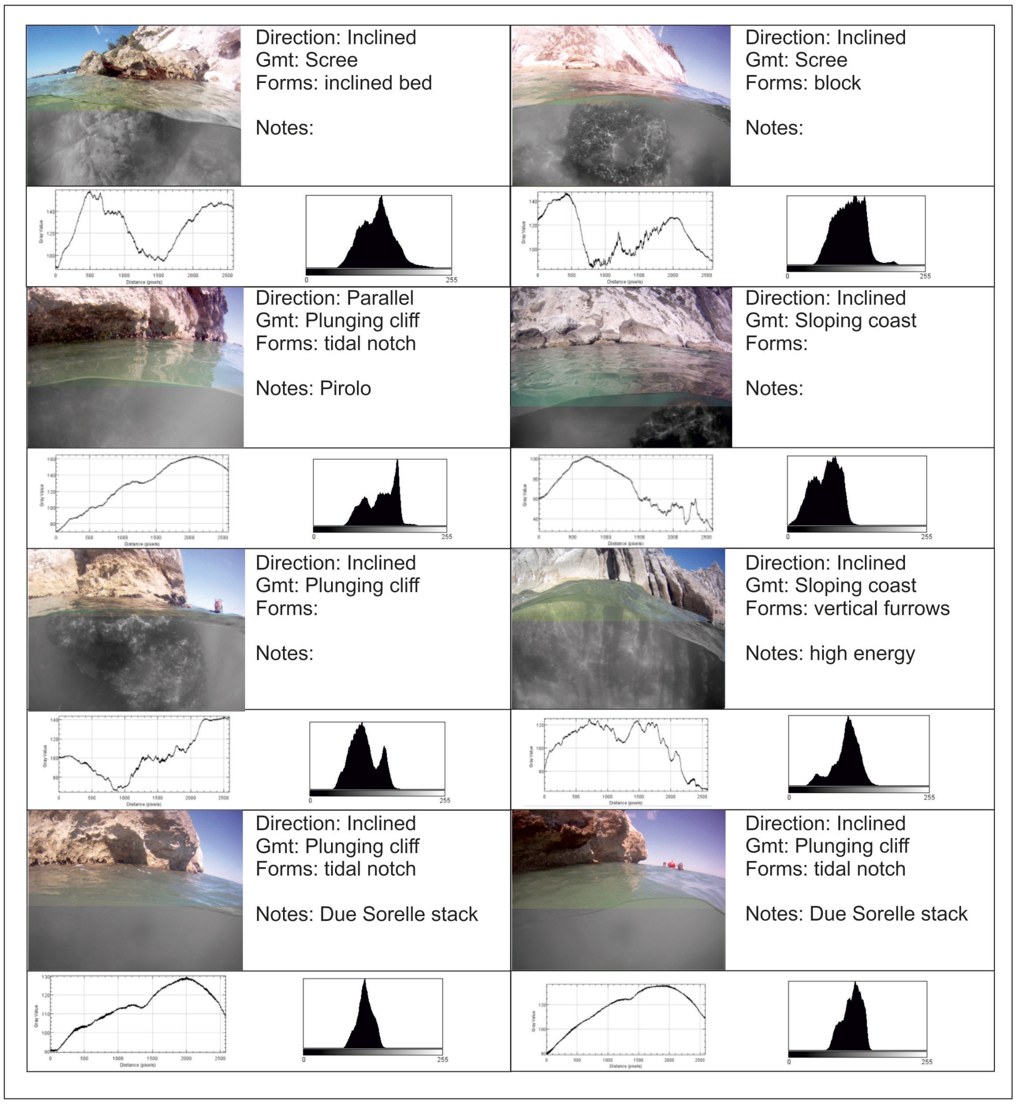
The tide ranged between ± 5 cm during the surveying period, while the wind blew constantly from the south with a maximum velocity of 4.0 m/s.

The seawater visibility was very low (see next paragraph for the quantitative data about the turbidity) due to the tail end of a storm occurred on the 15th and 16th of July 2017.

Visual analysis of time-lapse images

Image analysis was carried out on 267 selected images on a total of 3503 images (about 1 image/m). Some examples of images collected during the snorkel survey are reported in fig. 3 together with the visual interpretation. The parametrization of the selected images is summarized in the pie charts in fig. 4.

The statistical analysis on the 20% of the selected images showed that the standard deviation of greyscale in the histogram values is lower than 20 for images with high turbidity, while it is higher than 20 with low tur-



Direction: Inclined
Gmt: Scree
Forms: inclined bed

Notes:

Direction: Inclined
Gmt: Scree
Forms: block

Notes:

Direction: Parallel
Gmt: Plunging cliff
Forms: tidal notch

Notes: Pirolo

Direction: Inclined
Gmt: Sloping coast
Forms:

Notes:

Direction: Inclined
Gmt: Plunging cliff
Forms:

Notes:

Direction: Inclined
Gmt: Sloping coast
Forms: vertical furrows

Notes: high energy

Direction: Inclined
Gmt: Plunging cliff
Forms: tidal notch

Notes: Due Sorelle stack

Direction: Inclined
Gmt: Plunging cliff
Forms: tidal notch

Notes: Due Sorelle stack

FIG. 3 - Example of selected time-lapse images along the Mt Conero coastline. The lower part, which represents the submerged part, of the image is reported in greyscale. Beside the image, we reported the number of the selected image, the coordinates, the direction of acquisition with respect to the coastline, the predominant geomorphotype, coastal forms of key importance. Below the images, we reported the plot profile and the histogram of the submerged part.

bidity. Moreover, images with smoothed plot profiles (es. fig. 3) have higher turbidity than images with rough profiles (es. fig. 3). The visual interpretation of time-lapse images shows that the turbidity is very high in the 55% of the selected images, 37% are low-defined, while 8% are well-defined (fig. 4A).

Most of the selected images show at least half image above the sea level (38%), or images captured mostly above the sea level, in order to compensate the high seawater turbidity during the survey (fig. 4B).

Image analysis shows that most of the selected images (51%) were collected inclined to the coastline, while 38% were collected normal to the coastline (fig. 4C). The remaining part was collected parallel to the coast.

Most of the studied coast has a slope >60° (66%) or between 30° and 60° (31%), while only 3% is less than 30° above the sea level (fig. 4D). The same slope trend is below the sea level (up to 79% >60°) (fig. 4 E).

Coastal morphotypes and Tn

In fig. 5, the location and extent of the coastal morphotypes are reported. In particular, the snorkel survey, together with satellite images, showed that the 23% of the studied coastline is interested by up to 100 m-high plunging cliffs (fig. 5a), with 0.5 m to 1 m maximum depth at the submerged toe. Cliffs cover the 5% of the total lenght, while sloping coasts cover the 2%. They were surveyed just in front of the Due Sorelle stacks. The 42% of the coastline is interested by screes, which are very common morphotype due to the lithological and morphostructural setting of the coast. Only the 6% of the coast is interested by flat shore platforms, however backed by high cliffs. On the contrary, pocket beaches occur along the 22% of the coastline, among which the Due Sorelle and Forni beaches (fig. 5a) are the most important and best developed.

The snorkel survey allowed to recognize 4 sites where modern Tn occur (Table 1, fig. 5a). The tidal notch is carved along small sectors of plunging cliffs in which the Scaglia

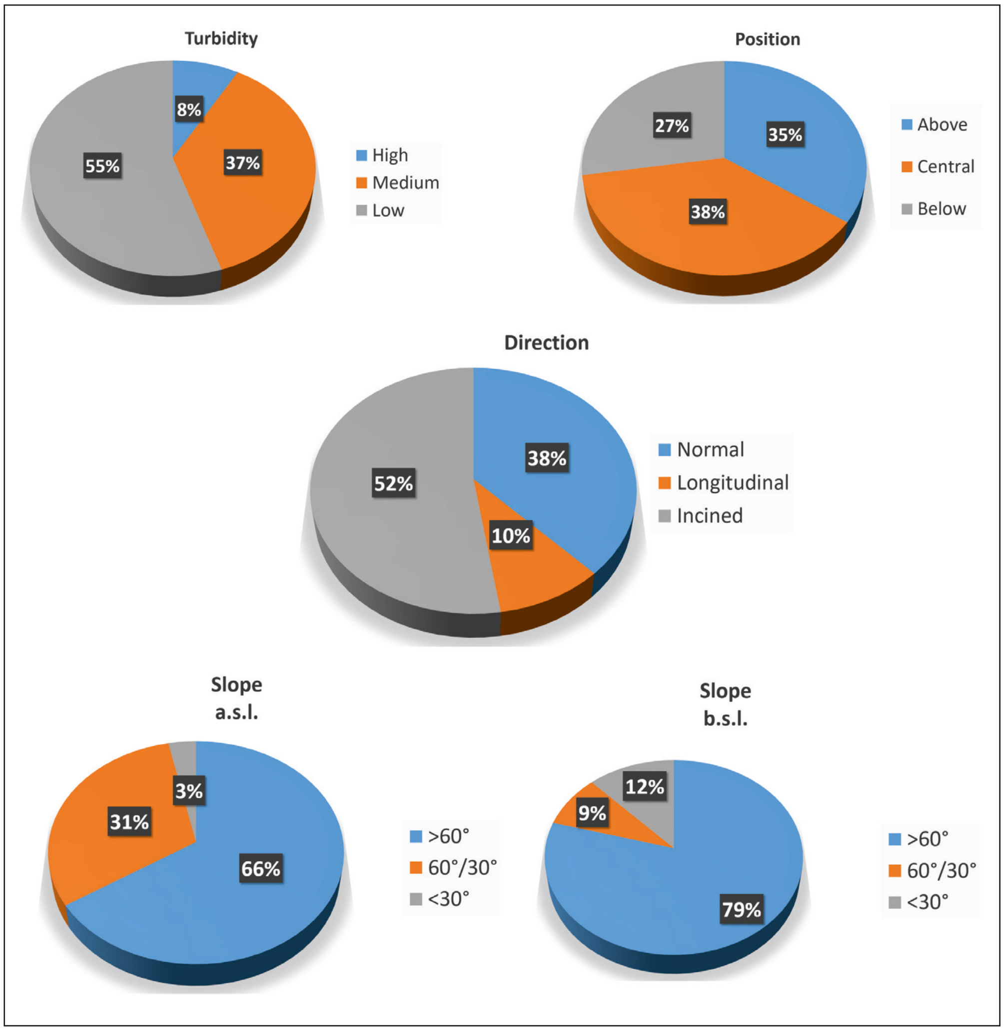


FIG. 4 - Pie charts of the parameters analyzed in the time-lapse images. A) Turbidity (high, medium, low); B) position of the image with respect to the sea level (above, central, below), C) direction of acquisition (normal, inlined, parallel), D) slope of the coast above the sea level; E) slope of the coast below the sea level.

Rossa Fm. outcrops, while it is completely lacking on collapsed blocks or Maiolica outcrops. The direction of exposure of the coast ranges from east to south-east (Table 1).

At the Pirolo coast reach, the average tidal notch width is 1 m, while its depth is about 0.5 m (fig. 6A). Here the notch takes the form of a not-well carved roof notch. The bottom depth is about 1.5 m b.s.l. As observed during the survey, the submerged part of the notch is smooth and there are many rounded blocks at the sea bottom. We report the presence of *Lithophyllum*, *Mytilus galloprovincialis* and *Patella cerulea*.

At Due Sorelle seastack, the tidal notch is well-carved along the entire perimeter of the stacks. The average notch width ranges from 0.7 m to 1.0 m, while the notch depth is 0.50 m (fig. 6B). The average bottom depth is about 2.0 m b.s.l.

Close to the cave named Grotta degli Schiavi, the tidal notch is carved on the plunging cliff (fig. 6C). The rock surface is very smoothed. We could not observe the sea bottom because of the turbidity. We report the presence of *Ulva lactuca*.

At the Vela seastak, the notch is 1.0 m wide and 0.60 m deep (fig. 6D). It is better carved in the exposed part.

Terrestrial geomorphological survey

The terrestrial geomorphological survey allowed to better delineate some landforms already reported in literature for the study area (Coltorti & *alii*, 1987; Fruzzetti & *alii*, 2011; Aringoli & *alii*,2014; Savelli & *alii*, 2017; Mastronuzzi & *alii*, 2017) and to map for the first time, thank to the very detailed scale of the targeted study, all those minor features that compose the complex and nested coastal geomorphological system at the Conero area, mainly related to coastal and gravitaty-induced processes (fig. 1; fig. 7). Sub-vertical cliffs and bays, interested by several landslides both active and dormant, are the main geomorphological features (fig. 7a). The poorly developed beaches and pocket beachesare fragmented by either rocky coastal cliffs plunging directly on the sea or landslide deposits (fig. 7a-d). Beaches are composed by coarse materials, namely blocks and gravels, mostly produced by gravity-induced slope processes (fig. 7d).

The entire rocky study area is affected by different types of landslides, which produce abundant landslide deposits along the coasts (fig. 1, fig. 7a-d, fig. 8). Rockfalls are common and recurrent in the lower part of slope be-

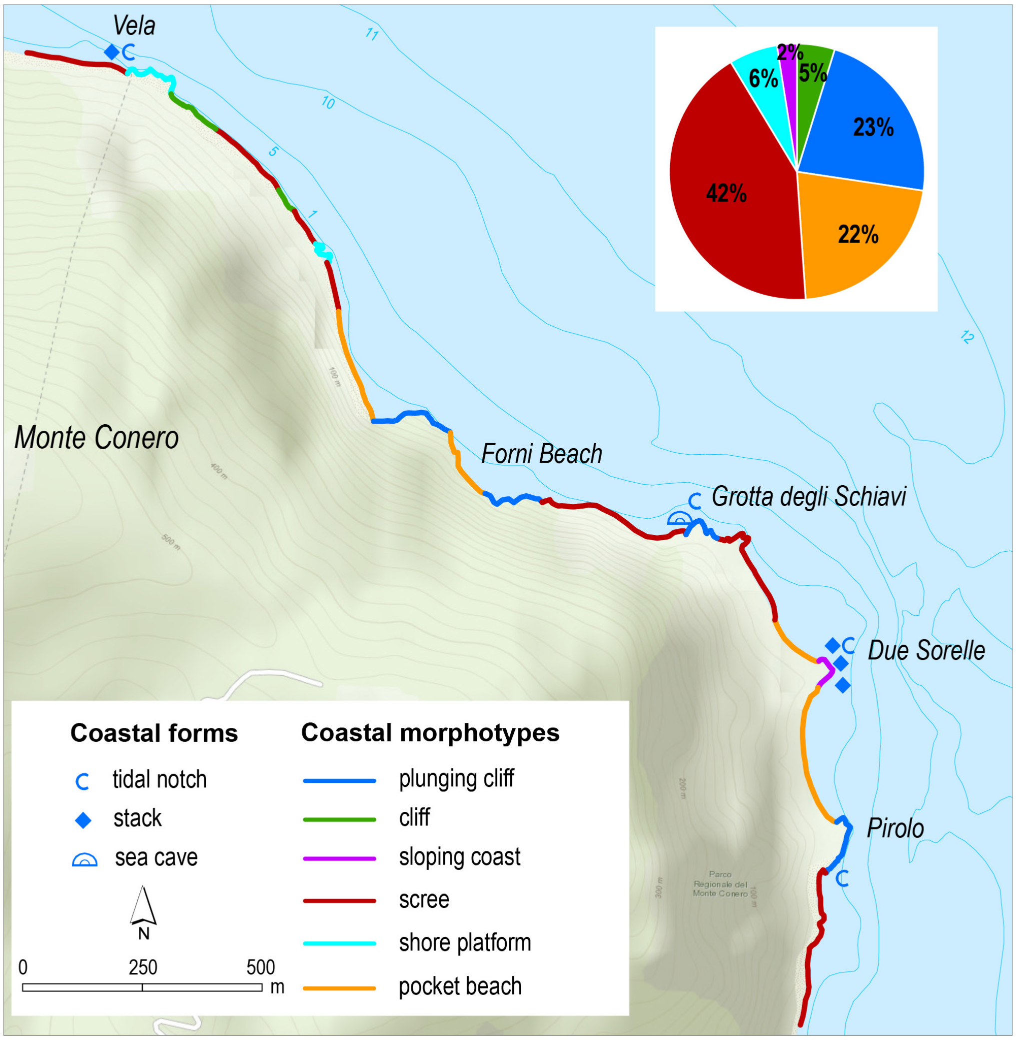


FIG. 5 - A) Map of the morphotypes along the studied coastal sector of Mt Conero. The pie chart represents the percentage of geomorphotypes surveyed along the snorkel path; B) Coastal stretch surveyed, the yellow line represents the route of the snorkel survey with time-lapse images, while the red line represents the remaining part of the route.

TABLE 1 - Morphometric parameters of Tn along the Mt Conero coastline.

ID	Site	Survey point	WGS84 coordinates (lat°; long°)	Lithology	Average notch width (m)	Notch depth (m)	Direction of Exposure	Notes
1	Pirolo	742	43.544213; 13.627988	Scaglia rossa	1.00±0.10	0.50±0.10	SE	not well carved
2	Due Sorelle 1	746	43.548247; 13.628141	Scaglia rossa	1.00±0.10	0.50±0.10	E	/
3	Grotta degli Schiavi	756	43.550709; 13.624537	Scaglia rossa	0.70±0.10	0.70±0.10	E	/
4	Vela	765	43.559421; 13.609265	Scaglia rossa	1.00±0.10	0.60±0.10	E	/

tween Vela sea stack and Grotta degli Schiavi, whereas rockslides are dominant at North of Vela and between Grotta degli Schiavi and Due Sorelle. Landslides are favoured by low values of persistence of discontinuities and by the presence of dip direction strata values very similar to slope orientation, that favour extensive phenomena. Areas with diffuse rocky slope instabilities, characterized by rock slope creep and slip-buckling slope phenomena (sensu Chigira, 1992 and Qin & *alii,* 2001) without evident accumulation of deposits, prevail in the upper part of slopes at South of Vela and between Due Sorelle e Pirolo. Debris flows are rare and do not exceed 2% of the total area affected by landslide processes.

FIG. 6 - Tn at A) Pirolo. The maximum retreat point is at -0.5 m m.s.l.; B and C) present-day tidal notch at Due Sorelle; D) view of the submerged passage between the coast (right) and the stack (left); E) tidal notch at Grotta degli Schiavi.

The gravity-induced phenomena are the source of an abundant production of rock blocks of various sizes, subsequently fragmentated and reshaped by the sea action (fig. 7a). At the base of the rocky cliff, a continuous belt of talus slope deposit is the result of the erosional processes in the upslope zone of the coastal cliff (fig. 7a-b). The surface of the talus deposits is affected by secondary landslide phenomena, while its base is undermined by sea action during storm events, producing debris and rock falls. The primary instability of the cliff is strictly controlled by litho-structural factors, and just few and limitated zones along the cliff are subjected to the prevailing action of undercatting due to the sea actions. Moreover, in correspondence of main rock discontinuities small natural caves occur.

Seastacks (fig. 7a-b) and discontinuos surf bench platforms (fig. 7c) are also observable along the coastal stretch. Seastacks are located at short distances from the coastline (<100 m) and are separated from the mainland as a result of landslide runout or due to the selective erosion on less resistant formations (i.e. Marne a Fucoidi Fm.). An example of the latter is the Due Sorelle seastacks (fig. 5a). Surf bench platforms are present in the northern sector of the area investigated, where seaward gently sloping emerged surface of limestone layers are shaped by backwashing waves.

Geomorphic marker of the past sea levels, such as remnants of late Quaternary marine terraces and hanging tidal-notches are absent along the whole analysed terrestrial sector of the Mt. Conero.

Geo-Structural data

The approaches to investigate the cliffs dynamics are mainly represented by rock mass characterization in terms of structural control of the fractures, mechanical properties of the rock masses, waves action and general weathering processes of the sea water and moisture. Planar and wedge failures are localized in the limestone masses, where the structural surfaces (fractures and bedding) generally bound blocks with an intersection line dipping through the free surface. Rockslides are related to failure planes, concentrated in the low-cohesion ma-

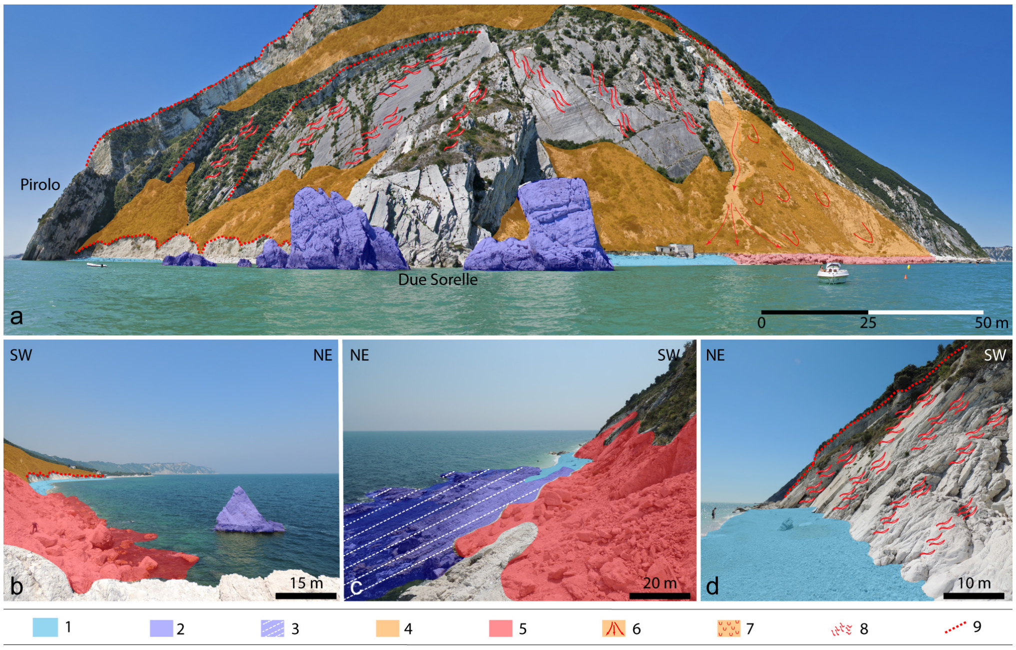


FIG. 7 - Coastal and gravitaty-induced landforms surveyed along the terrestrial sector of the Mt Conero. 1: Beach; 2: Seastack; 3: Surf bench platform; 4: Talus deposit; 5: Landslide due to rockfall; 6: Landslide due to debris flow; 7: Landslide due to rockslide; 8: Diffuse rocky slope instability; 9: Edge of scarp.

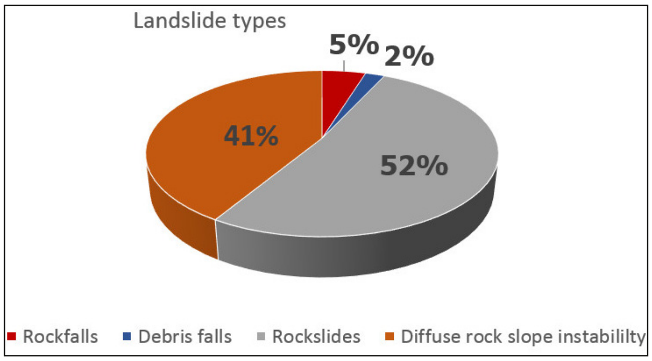


FIG. 8 - Percentange distribution of landslide types occurring in the study area.

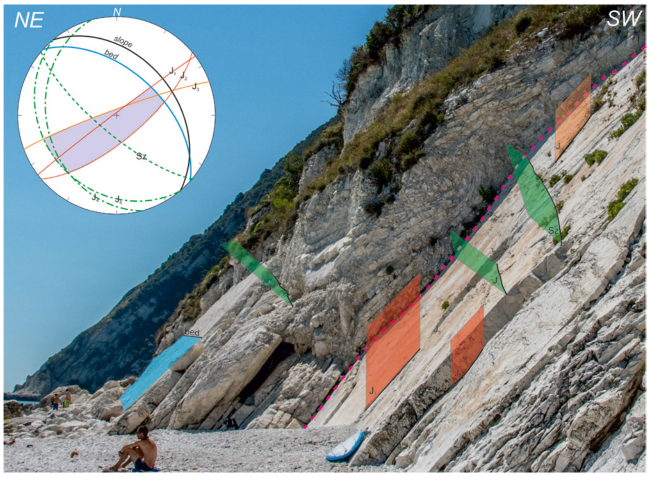


FIG. 9 - Kinematic analisy of the rocky slope along the coast hundred meters SE of Vela. Lower hemisphere equal area stereonet of the main discontinuities planes. Sets of subvertical joints – J1, J2 and J3 - guide the blocks sliding along the slope (grey area), while the system of joints J4 and J5 , associated with a diffuse shear zones – Sz - control the upper fissure that favorite the interbedding slip in the marly horizonts.

terial like marls. The kinematic analysis show that two sets of subvertical joints striking ENE-WSW (J1-J3 of fig. 9) guide the blocks along the slope while a system of joints oriented NW-SE (J4 and J5 of fig. 8) associated with a diffuse shear zones (Sz of fig. 9) control the upper fissure that favorite the interbedding slip in the marly horizonts. The weakness of the rock masses is controlled by the physical properties of the rocks and in particular by the degree of the moisture, because the water content and degree of weathering reduce the effective normal stress on the weakness planes, resulting in a more less stable slope than dry conditions. The pore fluid pressure related to the rain or sea action can play an important role on the stability of the cliffs significantly reducing the compressive and tensile strength of the rock mass. The measuments of the effective compressive strength measured on the limestone show a significant reduction from 50 MPa in dry conditions to 10 MPa in wet rocks (fig. 10).

DISCUSSION AND CONCLUSIONS

New observations carried out on specific markers related to the present and past sea levels, such as Tn, together with a detailed structural and geomorphological inland survey, allowed to discuss the morphoevolution of the Mt Conero area in the historical times. For the first time, a detailed snorkel geomorphological survey supported by geo-structural analyses allowed to underline the severe control of litho-structural factors on the morphodynamics and related morphotypes along the cliffs.

The analysis of time-lapse images collected during the survey permitted to define in detail the location of several sites, spreaded along the coastline between the Pirolo spur and the Vela seastack, where Tns occur. Due to the low turbidity of the sea, field observations collected during the survey provided useful data for the submerged part of the notch and the sea bottom in front of it. Tn provide constraints for the historical stability (last 500 years or more) of the sea cliffs where they have been shaped (e.g. Pirolo, Due Sorelle, Vela) or they can be witness of the relative sea level changes, in particular on hard and resistant rock masses.

The sea level model (Lambeck & *alii*, 2011) reported in fig. 11 shows that, considering a depth of the sea bottom of about 1 m between the studied seastacks and the mainland and no vertical tectonic movements, the seastacks of Due Sorelle and Vela remained connected to the mainland until about 2-2.5 ka BP. Considering a maximum tectonic uplift of 0.18 mm/a recorded along the northern Marche coast (Troiani & Della Seta, 2011 and reference therein), the sea reached the depth of 1 m later, therefore the stacks could be remained dried for further 600 years, roughly up to the Medieval Age. Finally, the present-day tidal notch started to be carved after the seastacks' drowning.

Lowering rates in limestones are in the order of hundreds of microns per year (Furlani & *alii*, 2009; Furlani & Cucchi, 2013) or more in presence of abrasion (De Waele & Furlani, 2013), as in the case of notches at the Grotta degli Schiavi or at the Pirolo spur, where there are several rounded blocks and pebbles on the sea bottom, at about 2 m b.s.l. Here, the maximum retreat point is at -0.5 m m.s.l. due to the abrasion. The occurrence of Tn is not continuous throughout the coastal sector, but they were observed just at small outcrops of micritic and well-stratified limestones of the Scaglia Rossa Fm. (fig. 1). This can be due to the major instability affecting the Maiolica Fm. outcrops along the cliff, but also it can be the result of selective erosion related to the different rock mass behavior between the Maiolica and Scaglia Rossa limestones. Even if no field data about local erosion rates is available, rock strength parameters in dry condition show that the Maiola Fm. is characterized by Uniaxial Compressive Strenght (UCS) of about 100 MPa, wheras the UCS of the Scaglia Rossa Fm. is about 50 MPa. Errors related to field measures (Table 1) do not allow to evaluate significant correlations between Tn depth and direction of exposure.

The complex and nested gravity-induced phenomena are characterised by both fast (such as rockfalls) and very slow mass movements (such as rock slope creep and slip-buckling slope phenomena, sensu Chigira, 1992 and

FIG. 10 - Vela seastacks. Lower hemisphere equal area stereonet of the main discontinuities planes: bedding (blue continuous line), joints systems J1, J2, J3 (orange continuous line); joints J4 and J5 with fractures Sz (green dashed lines). In the lower part, values of the uniaxial compressive strength (UCS) estimated with Schmidt hammer apparatus type L (impact energy of 0.735 Nm), respect the distance from the local sea level. The direction of impact with the rock wall is indicate.

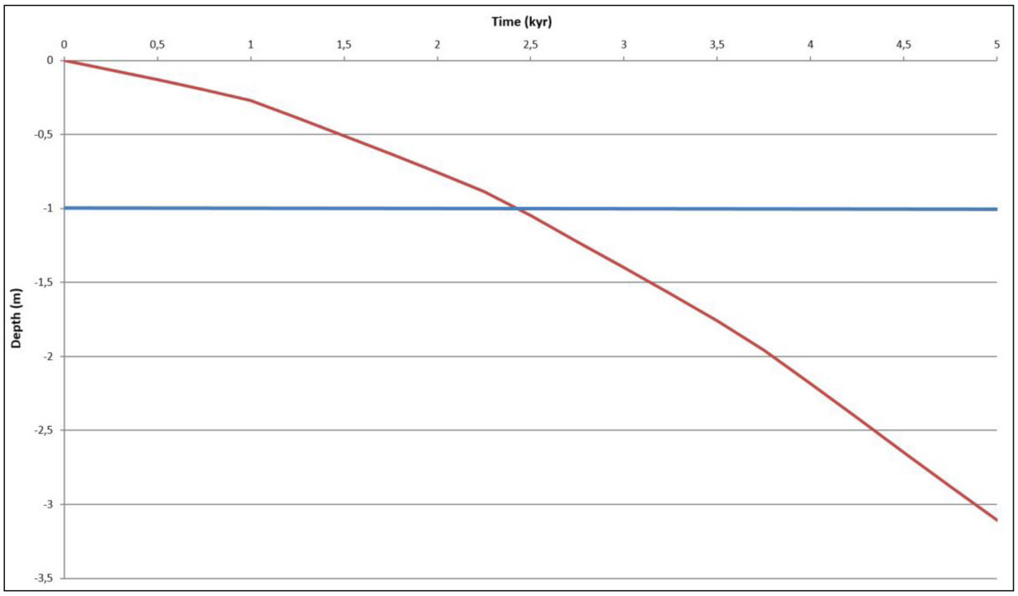


FIG. 11 - Sea level model from Lambeck & *alii* (2011) for the western Adriatic Sea at Ancona. The blue line at -1 m b.s.l. indicates the maximum depth between the Due Sorelle stack and the coastline. When the sea level was lower than 1 m, the stacks were connected to the land.

Qin & *alii* (2001). The rocky coast dynamics related to the cliff retreat and shore platform abrasion in the study area, as well as in mid Adriatic area, can be related to the low mechanical strength of the rocks and to the high fracturation that are amplified by the wave action. Rapid landlslides can be also triggered by earthquakes, as occurred on 22 August 2013 and 30 October 2016 when huge limestone blocks falled from Monte Conero respectively related to a M=4.4 and a M=6.5 earthquakes.

The combined action of climate change and slow-moving tectonic uplift (< 0.18 mm/a) generated, in the northern Marche coastal area, a well-exposed late Quaternary fluvial-to-coastal terrace staircase (Nesci & *alii*, 2012 and reference therein). The Conero area, although characterized by a more conservative morphostructure with respect to the whole northern Marche coastal area (Savelli & *alii*, 2017), does not display remnants of MIS5.5 or older marine terraces. The absence of active Tn outside summentioneted zones (Mastronuzzi & *alii*, 2017), as well as the absence of hanging or uplifted Tn or Tyrrenhian deposits and marine terraces, testify for an active and intense morphodynamic of the sea cliffs, mainly due to gravity-induced slope processes and the interrelated factors, such as geological factors or climate variations (Mortimore & *alii*, 2004).

Gravity-induced slope processes are common in the area. This may imply hazard situation for locals and tourists, such as landslide occurrences, or abrupt changes in coastal scenery, which can imply dramatic modifications of local geomorphological attractions, such as the recent arch collapse at Gozo, Malta (http://www.bbc.com/news/world-europe-39207196).

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