IT ISSN 0391 - 9838

Bollettino del Comitato Glaciologico Italiano - ser. 3

GEOGRAFIA FISICA e DINAMICA QUATERNARIA

An international Journal published under the auspices of the
Rivista internazionale pubblicata sotto gli auspici di

Associazione Italiana di Geografia Fisica e Geomorfologia
and (e) Consiglio Nazionale delle Ricerche (CNR)

recognized by the (*riconosciuta da*)

International Association of Geomorphologists (IAG)

volume 45 (2)
2022

COMITATO GLACIOLOGICO ITALIANO - TORINO
2022

GEOGRAFIA FISICA E DINAMICA QUATERNARIA

A journal published by the Comitato Glaciologico Italiano, under the auspices of the Associazione Italiana di Geografia Fisica e Geomorfologia and the Consiglio Nazionale delle Ricerche of Italy. Founded in 1978, it is the continuation of the «Bollettino del Comitato Glaciologico Italiano». It publishes original papers, short communications, news and book reviews of Physical Geography, Glaciology, Geomorphology and Quaternary Geology. The journal furthermore publishes the annual reports on italian glaciers, the official transactions of the Comitato Glaciologico Italiano and the Newsletters of the Intemational Association of Geomorphologists. Special issues, named «Geografia Fisica e Dinamica Quaternaria - Supplementi», collecting papers on specific themes, proceedings of meetings or symposia, regional studies, are also published, starting from 1988. The language of the journal is English, but papers can be written in other main scientific languages.

Rivista edita dal Comitato Glaciologico Italiano, sotto gli auspici dell'Associazione Italiana di Geografia Fisica e Geomorfologia e del Consiglio Nazionale delle Ricerche. Fondata nel 1978, è la continuazione del «Bollettino del Comitato Glaciologico Italiano». La rivista pubblica memorie e note originali, recensioni, corrispondenze e notiziari di Geografia Fisica, Glaciologia, Geomorfologia e Geologia del Quaternario, oltre agli Atti ufficiali del C.G.I., le Newsletters della I.A.G. e le relazioni delle campagne glaciologiche annuali. Dal 1988 vengono pubblicati anche volumi tematici, che raccolgono lavori su argomenti specifici, atti di congressi e simposi, monografie regionali sotto la denominazione «Geografia Fisica e Dinamica Quaternaria - Supplementi». La lingua usata dalla rivista è l'Inglese, ma gli articoli possono essere scritti anche nelle altre principali lingue scientifiche.

INDEXED/ABSTRACTED IN: Bibliography & Index of Geology (GeoRef); GeoArchive (Geosystem); GEOBASE (Elsevier); *Geographical Abstract*: *Physical Geography* (Elsevier); GeoRef; Geotitles (Geosystem); Hydrotitles and Hydrology Infobase (Geosystem); Referativnyi Zhurnal.
Geografia Fisica e Dinamica Quaternaria has been included in the Thomson ISI database beginning with volume 30 (1) 2007 and now appears in the Web of Science, including the Science Citation Index Expanded (SCIE), as well as the ISI Alerting Services.

HOME PAGE: http://gfdq.glaciologia.it/ - CONTACT: gfdq@dst.unipi.it

Printed with the financial support from (pubblicazione realizzata con il contributo finanziario di):

– Comitato Glaciologico Italiano
– Associazione Italiana di Geografia Fisica e Geomorfologia
– Ministero dell'Istruzione, Università e Ricerca
– Consiglio Nazionale delle Ricerche
– Club Alpino Italiano

Geogr. Fis. Dinam. Quat.
45 (2022). 221-228, 5 figg., 2 tabb.

DOI 10.4461/ GFDQ.2022.45.10

Marta PAPPALARDO [1*], Ramon BLANCO CHAO [2] & Giulia PIZZO [1]

POTHOLES AS EVIDENCE OF ABRASION PROCESS: INVESTIGATIONS ON AN ATLANTIC (SPAIN) AND A MEDITERRANEAN (ITALY) COAST

Abstract: Pappalardo M., Blanco Chao R. & Pizzo G., *Potholes as evidence of abrasion process: investigations on an Atlantic (Spain) and a Mediterranean (Italy) coast.* (IT ISSN 0391-9838, 2022).

Potholes are cylindrical depressions in rocky substrates, the genesis of which is connected to the presence of two elements: sediments and water energy. Coastal potholes have been less studied than stream potholes, for which a model of enlargement triggered by the vortex motion of water was developed. The main factors that determine the formation of potholes are bedrock type, geological structure, the presence of sediments and the occurrence of mechanical erosion, namely abrasion, traditionally considered responsible for shaping the pothole itself. The aim of this work is to investigate the role of abrasion and the effect of other factors, such as the amount of sediments, in shaping potholes on shore platforms or other flat surfaces along rocky coasts. Study sites were selected in two different landscapes: the Atlantic coast of NW Spain and the Mediterranean coast of NW Italy. Five potholes were randomly selected in each study site. Abrasion results in an increase of mechanical strength of the rock that can be measured with a durometer such as the Equotip. Rock hardness was tested in the investigated potholes along cross-shore oriented transects and the amount of sediment content in each pothole was analyzed and related to the pothole morphometry. Abrasion was considered effective in specific tracts of the profile where hardness values proved to be particularly high. Data obtained in most of the potholes showed a common pattern: they underlined a change in hardness along the profile and showed the effectiveness of the abrasion process on the bottom and on the highest part of the walls, mainly on the landward side. It was also demonstrated that when a pothole is actively developing due to abrasion, an equilibrium between the amount of sediments and wave energy exists, that can be quantified through an index. Our work contributes to the quantitative knowledge of the process of abrasion as responsible of the genesis of coastal potholes.

[1] *Department of Earth Sciences, University of Pisa, Italy.*

[2] *Department of Geography, Faculty of Geography and History, University of Santiago de Compostela, Spain.*

* *Corresponding author: M. Pappalardo (marta.pappalardo@unipi.it)*

The Authors acknowledge the following mobility programs: PDI Outgoing University of Santiago de Compostela and Visiting Fellows Program, University of Pisa (benefited by R. Blanco Chao); Mobility Program for the development of final thesis abroad, University of Pisa (benefited by G. Pizzo). Their gratitude goes as well to the students of the Pisa University Master Degree in Environmental Sciences for helpful support in field activities.

Key Words: Rocky coast, Cylindrical depression, Shore platform, Wave energy, Mechanical erosion, Mediterranean, Atlantic.

Riassunto: Pappalardo M., Blanco Chao R. & Pizzo G., *L'effetto dell'abrasione nella genesi delle marmitte: due casi di studio sulle coste atlantiche (Spagna) e mediterranee (Italia).* (IT ISSN 0391-9838, 2022).

Le marmitte sono depressioni cilindriche presenti su substrati rocciosi, la cui genesi è connessa alla concomitanza di due elementi: la presenza di sedimenti e l'energia di un flusso idrico. Le marmitte costiere sono state meno studiate di quelle presenti lungo gli alvei fluviali, per le quali è stato sviluppato un modello genetico secondo il quale l'erosione agisce attraverso moti vorticosi dell'acqua nella cavità. I fattori principali che determinano la formazione delle marmitte sono la litologia del substrato, la struttura geologica, la presenza di sedimenti e l'efficacia dell'erosione meccanica, ovvero dell'abrasione, tradizionalmente considerata il processo responsabile dell'escavazione della marmitta. Lo scopo di questo lavoro è quello di studiare il ruolo dell'abrasione e l'effetto di altri fattori, quali l'entità dei sedimenti, nel modellamento delle marmitte sulle piattaforme litorali o su altre superfici rocciose spianate lungo le coste rocciose. Le aree di studio sono state scelte in zone morfologicamente dissimili: l'estremità nordoccidentale del litorale Atlantico spagnolo e la costa mediterranea dell'Italia nordoccidentale. In ciascuna area di studio sono state selezionate con criterio casuale cinque marmitte. L'effetto dell'abrasione al loro interno si manifesta in un aumento della durezza della roccia, misurabile con un durometro tipo Equotip. Nelle marmitte studiate è stato testato il valore della durezza della roccia lungo transetti orientati perpendicolarmente alla linea di costa; l'entità dei sedimenti presenti all'interno di ciascuna marmitta è stata altresì misurata e messa in relazione con i caratteri morfometrici della stessa. L'abrasione è stata considerata efficace in tratti specifici lungo il transetto, in corrispondenza dei quali i valori di durezza sono risultati molto elevati. I dati ottenuti nella maggioranza delle marmitte hanno mostrato un andamento comune del parametro durezza, con valori più alti sul fondo della cavità e nel tratto più elevato delle pareti verticali, in particolare in quella verso terra. È stato anche dimostrato che, quando la marmitta è attivamente modellata dall'abrasione, vi è un equilibrio, quantificabile attraverso un indice, tra l'entità dei sedimenti presenti all'interno della marmitta e l'energia del flusso idrico. Questo lavoro contribuisce alla quantificazione del processo di abrasione responsabile della genesi delle marmitte costiere.

Termini Chiave: Coste rocciose, Depressione cilindrica, Piattaforma litorale, Energia del moto ondoso, Erosione meccanica, Mediterraneo, Atlantico.

INTRODUCTION

The formation of potholes on shore platforms or other flat surfaces along rocky coasts is a worldwide spread phenomenon. The role of abrasion in shaping them and of other factors, such as the amount of sediments, in driving this process are examined in this work.

Rocky coasts are exposed to several processes (Stephenson & *alii*, 2013), in particular marine and sub-aerial (weathering) processes, but also to bio-remodeling (Pappalardo & *alii*, 2016). Marine erosive processes are commonly subdivided in quarrying, wave impact and abrasion; the latter has been defined by Trenhaile (1987, p. 25) as 'the result of sweeping, rolling, or dragging of rocks and sand across gently sloping rock surfaces, or the throwing of coarse material against steep surface'. Hence abrasion is strictly connected to the presence of two elements: sediments and wave energy.

Rocky coasts display a number of weathering micro-mesoforms, such as tafoni, rockpools, honeycombs, potholes, all modeled by different processes (Trenhaile, 1987). These forms affecting coastal rocks, are hardly dependent on the climate regime under which the coast evolves but are rather dependant on the bedrock type and structure (Furlani & *alii*, 2014). The term "pothole" (Sunamura, 1992; De Pippo & Donadio, 1999) indicates a sub-cylindrical rockpool formed by waves in the spray zone fostering impact and dragging of sediments against the rocky substrate starting from a preexisting minor depression inside which wave energy creates a turbulence or even a vortex.

The main factors that determine the formation of a pothole are thus the bedrock type, the presence of sediments and the occurrence of mechanical erosion, namely abrasion, generally considered responsible for shaping the pothole itself. The shape and size of a pothole is also linked to geological structure as potholes are generally developed along fractures or joints pattern. Potholes form also along rocky river beds, where water flow is normally continuous; the modern works on potholes, aimed at modelling water and sediment motion inside them, are only considering stream potholes (Springer & *alii*, 2006; Ortega & *alii*, 2014).

The process of abrasion results in an increase of mechanical strength of the rock (Sunamura, 1992; Feal-Perez &Blanco-Chao, 2013; Stephenson & *alii*, 2013; Trenhaile, 2019), that can be measured with a durometer such as the Equotip (Viles & *alii*, 2011).

A great concern about ongoing climate change has emerged in the last years (https://www.ipcc.ch/report/sixth-assessment-report-cycle/). Climate models show a correspondence between global temperature and mean sea level, estimating an increase of 2° C and a rise of 0.11-0.77 m by 2100 (Church & *alii*, 2008), as a consequence of global warming.

The latest studies tend to link coastal erosion and climate change (Barnard & *alii*, 2017) in that an increase in global temperatures could be responsible of an increase in sea storminess. For this reason, we need to improve our understanding of marine processes driving the erosion of rocky coasts; this paper provides new observational and instrumental evidence of the effectiveness of mechanical abrasion driven by waves along the coast, and proposes a new quantitative index to state the activity of marine erosional processes responsible for potholes carving.

STUDY SITES

Study sites were selected in two different landscapes (fig. 1): the Atlantic coast of Spain (Caamaño) and the Mediterranean coast of Italy (Livorno). Caamaño is located at the north-western edge of the Iberian Peninsula (Galicia, Spain, 42° 39' 17.6" N, 9° 02' 27.1" W) and Livorno in NW peninsular Italy (43° 28' 25.5" N, 10° 19' 50.4" E).

The coast of western Galicia is characterized by shore platforms shaped on Palaeozoic igneous and metamorphic bedrock (Blanco Chao & *alii*, 2003), weathered and highly fractured, which facilitated marine erosion. Backing slopes are covered by periglacial deposits. Several elements of that rocky coast are considered inherited from past interglacial stages, with a sea level similar to today's (Trenhaile & *alii*, 1999). Precisely, the study site is situated at Caamaño (fig. 1a), where a coastal plain, stretches for 3-4 km between the mountains and the coast. The plain is bordered seaward by intertidal shore platforms developed in sub-vertical metamorphic and subordinately igneous rocks (Blanco Chao & *alii*, 2007). The Caamaño platform is situated at the geological boundary between granodiorites and micashists, with abundant aplitic dykes. It is controlled by the structure of metamorphic rock planes, which run NW-SE (325°-345°) and is crossed by sets of fractures running N-S, NE-SW and NW-SE. A supratidal rock ledge or ramp borders the platform inland, backed by a cliff with a scattered vegetation of halophite species, like *Armeria marittima* and *Crithmum maritimum*, growing on a sea cliff (fig. 2). The coast is exposed to waves mainly arriving from NW, generated by Atlantic low-pressure centers, with a 75 % of significant wave heights between 1 and 2.5 m, 14% between 2.5 and 5 m and maximum waves of up to 12 m. The tidal regime in Galicia is semidiurnal, with a mean tidal range of 2.5 m and a spring tidal range up to 4 m.

The coast of NW Italy is mainly characterized by rocky promontories joining wide coastal plains (Furlani & *alii*, 2014). The study area is morphologically known in the geological literature as Terrazzo di Livorno (Nisi & *alii*, 2003) a marine terrace developed during MIS 5, currently uplifted at 12 m asl. The terrace has a complex cover of marine and continental units (Ciampalini & *alii*, 2006) but in the study site (Calafuria, fig. 1b), which is located at its southernmost edge, only the bedrock outcrops, in the form of narrow supratidal sandstone platforms (Pappalardo & *alii*, 2017) representing the degradation of the terrace outer edge due to the action of gravity (Sciarra & *alii*, 2014), weathering processes (McBride & Picard, 2004; Chelli & *alii*, 2010) and bioerosion (Pappalardo & *alii*, 2016, 2018).

Moreover, these platforms have been extensively quarried since Roman Age (Galoppini & *alii*, 1996), and thus partly represent anthropogenic landforms. The bedrock sandstone, a variety of the Apennines "Macigno" Formation (Upper Oligocene–Lower Miocene) locally called "Arenaceous Flysch of Calafuria" (Lazzarotto & *alii*, 1990), consisting of medium- to thick-bedded siliciclastic turbid-

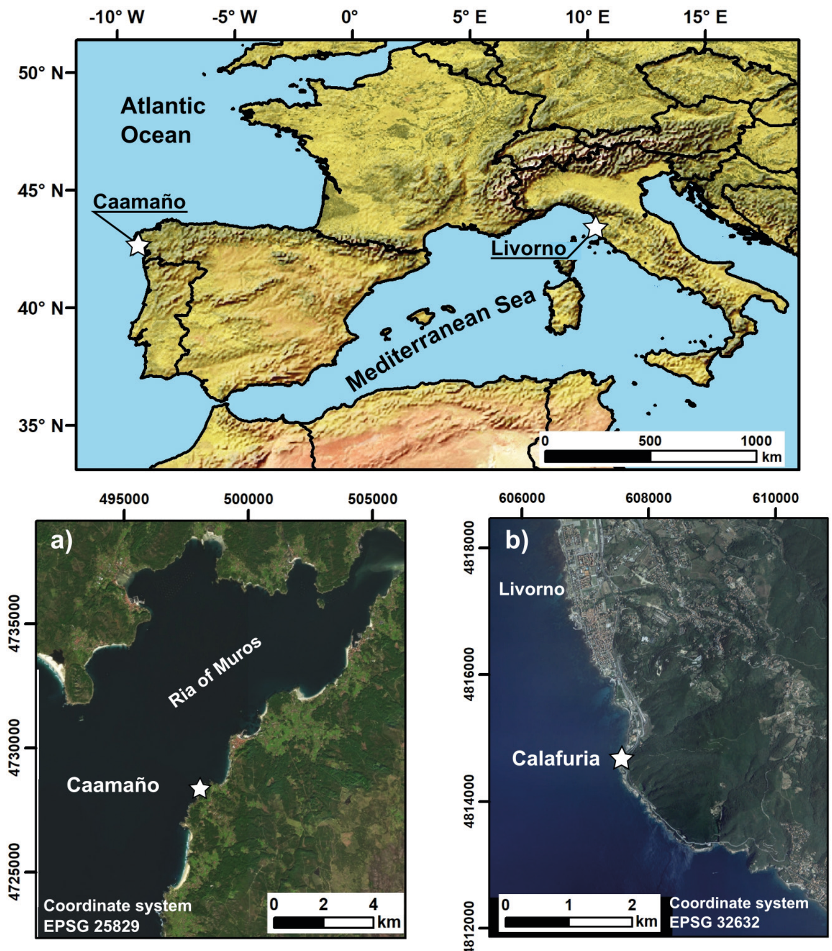

FIG. 1- Location of the two study sites, respectively along the Atlantic coast of Spain (Caamaño) and the Mediterranean coast of Italy (Livorno).

ites made of grey-brown sandstone. Three joint sets are consistent with the main fault directions: NW-SE, NS and NE-SW (Sciarra & *alii*, 2014).

The tidal regime in NW Italy is semidiurnal, with a mean tidal amplitude in Livorno of 0.5 m at spring tides that can be increased up to 0.6 due to the meteorological component; incoming waves reach the coast mostly from the 240° N direction with a maximum coastal significant wave height of 4.5 m (Pappalardo & *alii*, 2017).

The two sites of Caamaño and Livorno, although displaying a broad morphological similarity, are quite different in terms of bedrock type, tidal regime and wave climate. As regards the morphological processes currently acting on them, in Caamaño marine processes are prevalent, whereas in Livorno weathering and bioerosion are mostly responsible for current platform shaping. Nevertheless, potholes are present in both cases in the upper part of the intertidal and especially in the lower part of the supratidal (midlittoral). Investigating the mechanisms of potholes formation in two distinct and distant regions (i.e., at a great spatial scale), provides a good opportunity to isolate those common features that are independent of the boundary conditions. Conversely, the limited extent of each study site (few hundreds of m length) provides the opportunity to minimize intra-site-dependent factors due to small-scale inhomogeneities, that may affect the results of the investigation within each site.

METHODS

In this work, rock hardness (Moses & *alii*, 2014) will be used as a quantitative index of abrasion effectiveness, being abrasion the process responsible for potholes carving. Abrasion enhances the mechanical strength of rock by removing the weathered layer and reduces roughness (Feal-Perez &Blanco Chao, 2012). Consequently, rock hardness is greater where abrasion is more effective. Measuring hardness inside potholes, enables to identify, within each pothole, the spots where abrasion is greater and to compare the stage of activity between potholes.

When exposed to weathering processes, rock surfaces undergo surface or sub-surface change in their mechanical properties, that can be quantified using direct contact measurement techniques (Moses & *alii*, 2014), such as rock surface testing using durometers (Viles & *alii*, 2011) like the Schmidt hammer or the Equotip (ProceqR).

The Equotip is a testing device developed in 1970s in order to measure the hardness of many materials, mainly metals, and then implemented in other fields, like in geomorphology, where it has been used to assess the hardness of rocks (Aoki & Matsukura, 2007). This instrument exploits the dynamic rebound effect, to estimate the hardness value expressed as the Leeb number (L value) or Leeb hardness (HL).

Fig. 2 - Some of the ten randomly selected potholes respectively in Caamaño, Spain (CA - 2, 3 and 5) and Livorno, Italy (LI - 2, 3 and 5).

The instrument version Equotip-3 with a standard D impact device (Proceq®) is an electronic durometer, light in weight (780 g plus battery), with an impact energy of 11 Nmm, ideal for testing soft materials or the surface layer of rocks (Pappalardo & *alii*, 2018). The operation mode is based on the measurement of the impact velocity (vi) of the impact body and of its rebound velocity (vt). Data are combined in an a-dimensional index, the Leeb number (L), which corresponds to (vt/vi) x 1000 (Kompatscher, 2004) that the instrument yields after providing an automatic correction for the angle of impact. The value of L is therefore directly proportional to rock hardness. All the registered values are automatically stored and can be downloaded. A portable version of Equotip (Proceq®) is known as Piccolo 2, which has the same impact energy as the Standard D-type but is less performant in terms of data management on the device.

In this work both the Equotip-3 (Standard D-Type) and the Piccolo-2 were employed. The first has been used in experimental activity in Spain, while the second in Italy. A comparability test for the two instruments was conducted (Pappalardo & Blanco Chao, 2017) by acquiring data with the two instruments from the same profile of a pothole along the rocky shore of Calafuria using two testing methods: the Single Impact Method (SIM) with 10 readings distributed in an approximate area of 4 × 4 cm, and the Repeated Impact Method (RIM) with 15 repeated impacts

FIG. 3 - The different stages of the experimental protocol: potholes selection (a); extraction of water (b) and of sediments (c); hardness testing (d).

in three points taken within an area of 4 × 4 cm. For the statistical treatment two different methods were used: the average of the 10 readings in the SIM and the average of the three means of the 15 impacts in the RIM. The standard deviation was calculated from the 3 means. The repeated impact method provided an optimal overlap between values obtained using the two devices, hence, this method was chosen for conducting the study.

Five potholes of 40 to 100 cm width (fig. 2) and 30 to 140 cm depth were randomly selected in each study site (fig. 3a, within a spatially limited area, so that elevation and exposure conditions and bedrock type are homogeneous for all potholes.

In each pothole experimental manipulations were performed before hardness testing (fig. 3b-c): seawater was removed from the pothole and its amount was measured as a rough proxy of the pothole volume, sediments were removed from the pothole and weighed in the field using a dynamometer. These data were combined in an index (I) obtained by dividing the content of water in liters for the weight of sediments in hectograms, as follows: I = Water (l) / Sediments (hg). A long profile was identified along each pothole (from landward to seaward edge) and measuring points were marked on it with plaster. Up to 11 points were tested in Caamaño and up to 14 in Livorno for each pothole. Morphometric variables such as diameter (longer and shorter axis), depth and shape were measured. The inside walls of the pothole and its surface were visually described, and testing points were categorized according to their position within the biological zonation bands, i.e. the arrangement pattern of sessile biota assemblages along a rocky shore into elevation bands. Hardness testing was performed as soon as the rock surface had dried, using the Repeated Impact Method (RIM) described above (fig. 3d).

In order to minimize the effect of experimental variables, the L values were normalized to the maximum L value registered between all the ten potholes studied. The parameter (NLV), calculated through the formula: NLV = (1 - (L (1,2,3…10)/Lmax))*100, represents a proxy of rock hardness that can be used in order to quantitatively analyze pattern and the trend of hardness change along each profile and compare it between different potholes regardless their features and location.

RESULTS

In fig. 4 the NLV parameter calculated for each testing point is plotted against its distance from the pothole landward edge, represented on the horizontal axis. The blue lines represent the approximate potholes bottom profiles. Changes in NLV along each profile are normalized relative to the highest values obtained in a single plot in that profile. They consequently testify changes in hardness, regardless the measured hardness index of the rock, that is different in the two study sites. The higher NLV is, the more effectively abrasion acts.

NLV changes significantly along the profiles of all potholes (tab. 1). Although the index values from all testing points averaged for each of the 10 potholes are very similar, the spread between values obtained within each single pothole is remarkable in all cases, with a minimum value in CA-P-5 and a maximum in LI-P-4, suggesting that NLV is a suitable tool to highlight differences in abrasion effectivity. Moreover, the NLV range is not site-dependent, in that it cannot be used to differentiate Galician from Italian potholes.

In 9 cases out of 10, the highest NLV values are found in the testing points located: i) on the upper part of the landward inside wall, between the landward edge and the top of the filling debris, and ii) on the bottom of the pothole. In CA-P-1, conversely, the index decreases progressively from each of the edges towards the pothole bottom.

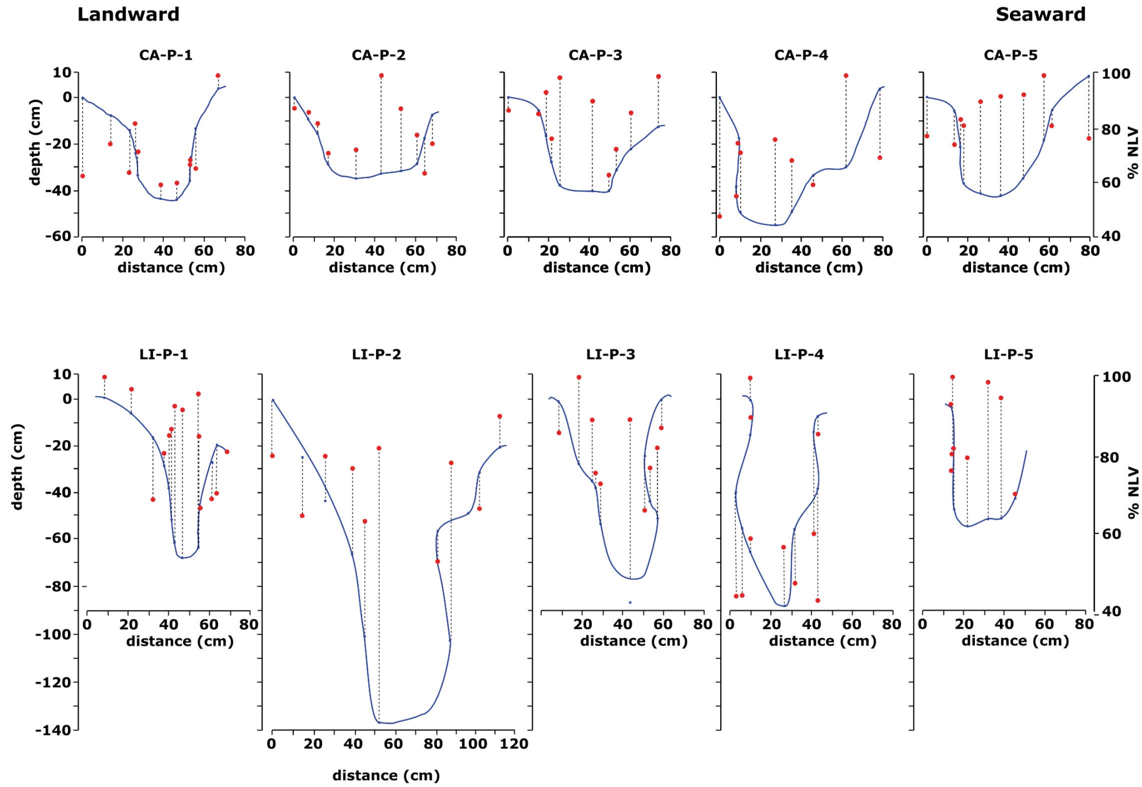

FIG. 4 - Diagrams for each of the 10 tested potholes showing, for each testing plot (red dots), the NLV parameter (vertical axis) plotted against its distance from the pothole landward edge (horizontal axis). The blue lines show the approximate potholes bottom profiles. CA codes are for the potholes tested in Caamaño and LI codes are for those tested in Livorno.

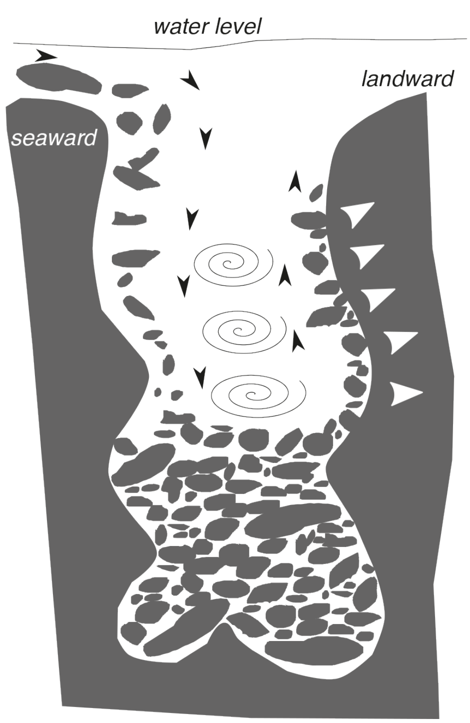

FIG. 5 - Sketch showing the movement pattern of water and grinding sediments inside the studied potholes, highlighting the part of the wall where abrasion processes are maximized (white arrows). The pothole outline is modified after Jennings (1983).

In tab. 2 the I index, corresponding to the ratio between the content of water (l) and the weight of clastic sediments (hg) inside the potholes is reported. According to I values potholes from both sites cluster in three groups: i) those having I < 1 are the potholes that are packed of sediments, those having I > 2, where sediments are scarce, and the intermediate group, in which there is a balance between sediments and water. The distribution of hardness values suggests the absence of abrasion CA-P-1, the only pothole the I value of which is exceeding 2.

DISCUSSION AND CONCLUSIONS

The analysis of the NLV parameter has pointed out that abrasion takes place similarly in Caamaño and Livorno test areas, in well identified parts of the pothole, which are the landward inside wall and the bottom. Abrasion is less effective at the base of the internal walls where, in conditions of low hydrodynamics, the rock is covered by the pothole-filling debris.

This evidence is consistent with the classical theory of potholes formation as triggered by debris-armored water vortex motion (Alexander, 1932; Sunamura, 1992), confirming, as pointed out by Shaocheng & *alii*, (2018), that the dynamic of the forming process is the same for marine potholes as for those developing in different environments. Water with grinders inside the pothole is subjected to a vortex motion which is responsible for abrasion of the

TABLE 1 - Normalized L value (NLV) measured in each test point of the five potholes tested respectively in Caamaño (CA-P- 1 to 5) and in Livorno (LI-P- 1 to 5).

Test point number	Pothole code									
	CA-P-1	CA-P-2	CA-P-3	CA-P-4	CA-P-5	LI-P-1	LI-P-2	LI-P-3	LI-P-4	LI-P-5
1	62	88	87	47	77	100	80	85	100	93
2	74	85	86	75	74	97	65	100	90	77
3	64	82	94	55	83	68	80	89	42	81
4	82	71	77	71	81	81	77	75	43	100
5	72	73	99	76	90	85	63	72	58	82
6	59	100	90	68	92	87	82	89	56	80
7	60	88	63	59	92	92	78	82	46	99
8	67	78	73	100	100	92	53	76	42	95
9	68	64	86	69	81	96	100	65	59	70
10	66	75	100		76	85	66	87	85	
11	100					66	90			
12						68				
13						70				
14						81				

TABLE 2 - The abrasion index (I) obtained from the analyzed potholes.

CA-P-1	CA-P-2	CA-P-3	CA-P-4	CA-P-5	LI-P-1	LI-P-2	LI-P-3	LI-P-4	LI-P-5
2.3	2.0	0.3	1.8	1.4	0.20	1.02	0.75	0.41	0.20

pothole bottom and its consequent deepening. More specifically this work demonstrates that the landward inside wall of potholes is more affected by abrasion than the opposite seaward wall. The landward wall, in fact, is exposed to direct waves energy and flux, being pushed against the landward wall in addition to the dynamic of the vortex motion. This is in agreement with the observed increased effectiveness of stream erosion in those fluvial potholes that are located in the proximity of the active fluvial channel (Ortega-Becerril & *alii*, 2017).

Conversely, our evidence that abrasion is less effective at the base of the internal walls challenges spiral motion model described by in Jennings (1983) to explain the enlargement of the pothole downwards and sideways, demonstrating that the effectiveness of grinders along the pothole walls decreases with depth. This can be explained considering that potholes dissipate flow energy and inhibit transport of sediments (Johnson & *alii*, 2007), that are accumulated mostly in the lower half of the pothole. The presence of patches unaffected by abrasion also explains the persistence of living biota inside the studied potholes (Maggi & *alii*, 2017).

According to the methodology applied in this work the potholes in Livorno are all affected by abrasion, whereas in Caamaño the only tested pothole with no evidence of abrasion at the bottom is CA-P-1, which according to the measured I index is overloaded with sediments. A crucial factor for potholes development is, besides those generally accounted for (Wang & *alii*, 2010), the balance between the amount of filling sediments and wave energy: if the pothole is overloaded with sediments, wave energy necessary to trigger their movement is achieved too seldom during the year.

Another result of this work that challenges previous literature (e.g. Abbott & Pottratz, 1969) is that the morphology of marine potholes is independent from rock hardness. In fact, results are equivalent in two study areas with very different bedrock features.

Feal-Perez & Blanco Chao (2012) pointed out that the abrasion process depends 'predominantly on the grain size of the abrasive agent'. Studying the flux of sediments inside and outside potholes, grain size, sorting and shape of grinding materials, relating them to abrasion patterns and effectivity is a future promising research topic. Achieving sufficient experimental evidence will enable the provision of input data for a reliable predictive model of potholes genesis and evolution along rocky shores.

Rock coast geomorphology has largely progressed over the last decades and one of its main goals, as stated by Naylor & *alii* (2010) is to 'identify and measure the process that are operating on rocky substrates'. This study gives a better knowledge of the abrasion process which determines potholes development. In a sea-level rising world processes driving potholes development deserve to be furtherly investigated, considering that the rate of abrasion in potholes is faster than ordinary wave action, but also that potholes have a relevant value as geodiversity components (Álvarez-Vázquez & Uña-Álvarez, 2017).

REFERENCES

ABBOT A.T. & POTTRATZ S.W. (1969) - *Marine pothole erosion, Oahu, Hawaii.* Pacific Science, 23 (3), 276-290.

ALEXANDER H.S. (1932) - *Pothole erosion*. Journal of Geology, 40, 305-337.

Álvarez-Vázquez M.Á. & de Uña-Álvarez E. (2017) - *Inventory and assessment of fluvial potholes to promote geoheritage sustainability (Miño River, NW Spain).* Geoheritage, 9 (4), 549-560.

Aoki H. & Matsukura Y. (2007) - *A new technique for non-destructive field measurement of rock-surface strength: An application of the Equotip hardness tester to weathering studies.* Earth Surface Processes and Landforms, 32, 1759-1769.

Barnard P.L., Hoover D., Hubbard D.M., Snyder A., Ludka B.C., Allan J., Kaminsky G.M., Ruggiero P., Gallien T.W., Gabel L., McCandless D., Weiner H.M., Cohn N., Anderson D.L. & Serafin K.A. (2017) - *Extreme oceanographic forcing and coastal response due to the 2015-2016 El Niño.* Nature Communications, 8, 14365.

Blanco-Chao R, Costa-Casais, M., Cortizas, A.M., Pérez-Alberti, A., Trenhaile, A.S. (2003) - *Evolution and inheritance of a rock coast: Western Galicia, Northwestern Spain.* Earth Surface Processes and Landforms, 28 (7), 757-775. doi: 10.1002/esp.496

Blanco-Chao R., Pérez-Alberti, A., Trenhaile, A.S., Costa-Casais, M., Valcárcel-Díaz, M. (2007) - *Shore platform abrasion in a para-periglacial environment, Galicia, northwestern Spain.* Geomorphology 83, 136-151. doi: 10.1016/j.geomorph.2006.06.028

Chelli A., Pappalardo M., Arozarena Llopis I., Federici P.R. (2010) - *The relative influence of lithology and weathering in shaping shore platforms along the coastline of the Gulf of La Spezia (NW Italy) as revealed by rock strength.* Geoorphology, 118, 93-104.

Church J.A., White N.J., Aarup T., Wilson W.S., Woodworth P.L., Domingues C.A., Hunter J.R. & Lambeck K. (2008) - *Understanding global sea levels: Past, present and future.* Sustainability Science 3, 9-22.

Ciampalini A., Ciulli L., Sarti G. & Zanchetta G. (2006) - *Nuovi dati geologici del sottosuolo del 'terrazzo di Livorno'.* Atti della Società Toscana di Scienze Naturali, Memorie Serie A, 111, 75-82.

De Pippo T. & Donadio C. (1999) - *Morphology, genesis and evolution of rockpools along Italian coasts.* Geografia Fisica e Dinamica Quaternaria, 22, 129-141.

Feal Pérez A. & Blanco Chao R. (2013) - *Characterization of abrasion surfaces in rock shore environments of NW Spain.* Geo-Marine Letters, 33, 173-181.

Furlani S., Pappalardo M., Gomez Pujeol L. & Chelli A. (2014) - *Chapter 7: The rock coast of the Mediterranean and Black seas.* Geological Society, London, Memoirs, 40, 89-123.

Galoppini R., Mazzanti R., Taddei M., Tessari R. & Viresini L. (1996) - *Le cave di arenaria lungo il litorale livornese.* Quaderni del Museo di Storia Naturale di Livorno, 14, 111-146.

Jennings J.N. (1983) - *Swirlholes and related bedrock river channel forms.* The Australian Geographer, 15, 411-414. doi: 10.1080/00049188308702846

Johnson, J.P. & Whipple, K.X. (2007) - *Feedbacks between erosion and sediment transport in experimental bedrock channels.* Earth Surface Processes and Landforms, 32 (7), 1048-1062.

Kompatscher M. (2004) - *Equotip-Rebound hardness testing after D. Leeb.* In: HARDMEKO 2004 Hardness Measurements Theory and Application in Laboratories and Industries 11-12 November, 2004, Washington, D.C., USA.

Lazzarotto A., Mazzanti R., Nencini C. (1990) - *Geologia e morfologia dei Comuni di Livorno e Collesalvetti.* Quaderni del Museo di Storia Naturale di Livorno, 11 (Suppl. 2), 1-85.

Maggi E., Rindi L., Dal Bello M., Fontanini D., Capocchi A., Bongiorni L., Benedetti-Cecchi L. (2017) - *Spatio-temporal variability in Mediterranean rocky shore microphytobenthos.* Marine Ecology Progress Series, 575, 17-29.

McBride, E.F. & Picard, M.D. (2004) - *Origin of honeycombs and related weathering forms in Oligocene Macigno Sandstone, Tuscan coast near Livorno, Italy.* Earth Surface Processes and Landforms, 29, 713-735. doi: 10.1002/esp.1065.

Moses C., Robinson D. & Barlow J. (2014) - *Methods for measuring rock surface weathering and erosion: A critical review.* Earth-Science Reviews, 135, 141-161.

Naylor L.A., Stephenson W.J. & Trenhaile A.S. (2010) *Rock coast geomorphology: Recent advances, and future research directions.* Geomorphology 114, 3-11.

Nisi M., Antonioli F., Dai Pra G., Leoni G. & Silenzi S. (2003) - *Coastal deformation between Versilia and the Garigliano plains (Italy) since the last interglacial stage.* Journal of Quaternary Science, 18, 709-721.

Ortega J.A., Gómez-Heras M., Perez-López R. & Wohl E. (2014) - *Multiscale structural and lithologic controls in the development of stream potholes on granite bedrock rivers.* Geomorphology, 204, 588-598.

Ortega-Becerril, J., Gomez-Heras, M., Fort, R., Wohl, E. (2017) - *How does anisotropy in bedrock river granitic outcrops influence pothole genesis and development?* Earth Surface Processes and Landforms, 42 (6), 956-968.

Pappalardo M., Buehler M, Chelli A., Cironi L., Pannacciulli F. & Qin Z. (2016) - *Quantitative estimates of bio-remodeling on coastal rock surfaces.* Journal of Marine Science and Engineering, 4, 37.

Pappalardo M., Cappietti L., Arozarena Llopis I., Chelli A. & de Fabritiis, L. (2017) - *Development of shore platforms along the NW Coast of Italy: The role of wind waves.* Journal of Coastal Research, 33, 1102-1112.

Pappalardo M., Maggi E., Geppini C. & Pannacciulli, F. (2018) - *Bioerosive and bioprotective role of barnacles on rocky shores.* Science of the Total Environment, 619-620, 83-92.

Pappalardo M & Blanco-Chao R. (2017) - *Abrasion effectivity in rock coast potholes.* In: IX Jornadas de Geomorfología Litoral (Menorca, 2017). Geo-Temas, ISSN 1576-5172.

Sciarra N., Marchetti D., D'Amato Avanzi G. & Calista M. (2014) - *Rock slope analysis on the complex Livorno coastal cliff (Tuscany, Italy).* Geografia Fisica e Dinamica Quaternaria, 34, 113-130.

Springer G.S., Tooth S. & Wohl E.E. (2006) - *Theoretical modelling of stream potholes based upon empirical observations from the Orange River, Republic of South Africa.* Geomorphology, 82, 160-176.

Stephenson W.J., Dickson M.E. & Trenhaile A.S. (2013) - *Rock Coasts.* In: Shroder J.F. (Ed.), Treatise on Geomorphology, Academic Press, San Diego, 10, 289-307.

Sunamura T. (1992) - *Geomorphology of Rocky Coasts.* Wiley, Chichester, 302 pp.

Trenhaile A.S. (1987) - *The Geomorphology of Rock Coasts.* Oxford University Press, Oxford, 384 pp.

Trenhaile, A.S. (2019) - *Rock Coast Processes.* In: Finkl C.W. & Makowski C. (Eds.), Encyclopedia of Coastal Science. Encyclopedia of Earth Sciences Series. Springer, Cham: 1454-1458.

Trenhaile A., Pérez-Alberti A., Martinez-Cortizas A., Costa-Casais M. & Blanco-Chao R. (1999) - *Rock coast inheritance: An example from Galicia, northwestern Spain.* Earth Surface Processes and Landforms, 24, 605-621.

Viles H., Goudie A., Grab S. & Lalley J. (2011) - *The use of the Schmidt Hammer and Equotip for rock hardness assessment in geomorphology and heritage science: A comparative analysis.* Earth Surface Processes and Landforms, 36, 320-333. doi: 10.1002/esp.2040

Wang W., Xu L., Wu Z. & Huang, S. (2010) - *Shape and spatial distribution features of marine potholes on the coast of Shenzhen, China.* Dili Xuebao/Acta Geographica Sinica, 65 (3), 320-330.

(Ms. received 26 June 2023, accepted 07 October 2023)