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MORPHOLOGY, GENESIS AND EVOLUTION OF ROCKPOOLS ALONG ITALIAN COASTS

ABSTRACT: DE PIPPO T. & DONADIO C., *Morphology, genesis and evolution of rockpools along italian coasts.* (IT ISSN 0391-9838, 1999).

Recent research has provided more knowledge on identifying rockpools along Mediterranean coasts and on understanding their genesis and evolution.

Observation of thirteen morphotypes falling into five different categories and some forms with intermediate features allowed a genetic-morphological classification to be proposed, partly bearing in mind descriptions furnished by other Authors in differing geographic sites. The observed rockpools may be found in any resistant substrate, in both emerged and submerged environments. They are generally circular in shape and show a general evolutionary trend towards spindle-shaped geometries.

Frequent phenomena of piracy, producing rejuvenated forms and/or large, complex rockpools, are observed in the different morphotypes. Their genesis and evolution are closely linked to changing environmental conditions and their reciprocal interaction. Bio-erosion, action of bio-constructor micro-organisms and precipitation of salts in rock pores are prevalent. This processes are accompained by physico-chemical erosion by both marine and meteoric waters and mechanical erosion by waves.

Climatic conditions, characteristics of the rocky substrate and degree of exposure to wave action also greatly influence the development of rockpools. In addition to currently evolving forms, «fossil» forms may also be observed on marine terraces, closely correlated with Pleistocene tectonic and eustatic events which brought the rockpools to location higher than the present-day sea level. They are now exposed to subaerial erosion, together with submarine remodelling or progressive sediment infilling at depth beyond 10 m.

KEY WORDS: Geomorphology, Coastal erosion, Quaternary, Mediterranean.

RIASSUNTO: DE PIPPO T. & DONADIO C., *Morfologia, genesi ed evoluzione delle pozze di scogliera lungo le coste italiane.* (IT ISSN 0391-9838, 1999).

Le ricerche svolte hanno permesso di fornire un contributo al riconoscimento delle pozze di scogliera presenti lungo le coste mediterranee ed alla comprensione della loro genesi ed evoluzione. L'osservazione di tredici morfotipi, ascrivibili a cinque differenti categorie, ed alcune forme con caratteristiche intermedie ha consentito di proporre una classificazione genetico-morfologica, tenendo tra l'altro conto di quanto descritto da altri Autori in diverse località geografiche.

Le pozze di scogliera osservate sono presenti su qualunque litologia resistente, sia in ambiente emerso sia subacqueo, presentando principalmente una forma circolare ed una generale tendenza evolutiva verso geometrie di tipo fusoidale.

Per differenti morfotipi sono stati osservati frequenti fenomeni di cattura che producono un ringiovanimento delle forme, generando pozze di scogliera complesse anche di grandi dimensioni.

La genesi ed evoluzione delle forme descritte sono risultate strettamente connesse ai differenti fattori ambientali ed alla loro mutua interazione. Importanti risultano i fenomeni di bioerosione, l'azione esercitata dagli organismi biocostruttori e la precipitazione di sali nei pori della roccia. Congiuntamente a tali processi risultano determinanti sia l'erosione fisico-chimica operata dall'acqua, marina e meteorica, che l'erosione meccanica del moto ondoso. Anche le condizioni climatiche, le caratteristiche del substrato roccioso e l'esposizione della costa rivestono grande influenza nell'evoluzione delle pozze di scogliera.

Oltre alle forme attualmente in evoluzione, sono state osservate sui terrazzi marini forme la cui posizione è strettamente correlata agli eventi tettono-eustatici pleistocenici; questi hanno portato le pozze di scogliera sia a quote superiori dell'attuale livello marino, dove sono esposte ai fenomeni d'erosione subaerea, sia a profondità oltre i 10 m, dove subiscono un rimodellamento o un progressivo colmamento.

TERMINI CHIAVE: Geomorfologia, Erosione costiera, Quaternario, Mediterraneo.

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INTRODUCTION

Rockpools, the small depressions so typical of the morphology of rocky coasts or the surface of present-day or older marine terraces eroded by the sea, must be considered important elements for proper understanding of the evolutionary phenomena which affected coastal environments. These morphotypes, extensively found in many localities, mainly in temperate and tropical areas, in coastal transition zones, and subject continually to sea spray, occur in all coastal areas, both tide- and wave-dominated, up to heights of 2-4 m. Fossil forms, sometimes masked by sediments, may be observed on ancient flat surfaces now located both under and above the present-day sea level. Their position is clearly due to ancient sea level highstands and lowstands, in turn partly related to tectonic dislocations involving coastal belts, mainly during the Quaternary.

The present work aims at supplying details allowing rapid *in situ* identification of such forms along the Mediterranean coasts and at understanding their complex genesis and diverse evolution. These features are also linked to lithology, layer dip, degree of fracturing and possible karstism, and also to the profile, gradient, orientation and exposure of the coasts in question. An attempt is also made here to analyse the roles played by climate, mechanical action by waves, chemical dissolution of meteoric and sea waters, and the biochemical action of lithophage, lithobiontic and lithoconstructor organisms, all of which represent further factors governing the formative cycle of rockpools.

PREVIOUS KNOWLEDGE

The term *vasque*, or the less common *flaque,* used by French Authors, generally refers to their basin-like aspect. Similarly, in English they are called *pools, flat-bottomed pools* or *flat-floored basins*, while *rockpool* (or *rocky pool*), *fluted lapies* or *lapiéz* and *solution pools* indicate not only the prevailing form but also the stony nature of the substrate and forms due to karstic genesis. The word *pan*, although also used to denote rockpools, refers to large subelliptical depressions with diameters ranging from 50 m to 5 km due to wind deflation, with barchan dunes on the leeward side, composing relict forms in desert areas (Garner, 1974). Forms similar to rockpools are the smaller (1-3 m) elongated ephemeral pools generated behind first-order berms during storms along the sandy-pebbly beaches of the Mediterranean. Italian Authors use the expressions *marmitta di evorsione* (derived from current terminology for fluvio-glacial environments: Castiglioni, 1982; Federici & Piacente, 1993), *marmitta di abrasione* (Romano & Sgrosso, 1992), *marmitta di erosione* or *vasca di corrosione*, the latter translated from the French (De Pippo & *alii*, 1998). These terms are all equivalent to the English word *pothole* (Sunamura, 1992), indicating the characteristic subcylindrical or hemispheric shape, the genesis of which is due to the high-energy hydrodynamics of wave motion in spray zones, causing impact and abrasion of transported detritus against the rocky bottom (corrasion). Issel (1918) was perhaps the first to use the term *rockpool* in a work describing its biological features; Battistini (1986) described in detail the sizes of some of these forms, resting on limestone and calcarenitic abrasion platforms (eolianites) in southern Madagascar, where the tidal range is about 1.5 m.

In the present work, analysis of genetic features indicates both bioconstructed and erosional forms, the latter showing evidence of mixed biological, mechanical and dissolutive erosion. Rockpools with reverse-gradient bottoms had already been reported in flat basalt surfaces in tropical regions (Wentworth, 1938; Hills, 1949; Guilcher & *alii*, 1962) and on Quaternary calcarenites (eolianites) along the Atlantic coastline of Marocco (Guilcher & Joly, 1954).

In agreement with previous Authors, Battistini (1986) attributes their origin to the greater resistance of rock near the waterline, due to the precipitation of calcite in pores and cracks, and to the presence of extensive algal covers and bioconcretions. The origin of coastal erosional forms is also linked to superficial dismantling by lithobiontic micro-organisms (epiliths, chasmo-, crypto- and eu-endoliths) the action of which gives rise to holes and cracks in limestone rocks (Golubic, 1981; fig. 1). The mechanisms of biological micro- and macro-erosion contribute towards the morphogenesis of limestone coasts in several geographic areas (Spencer, 1988). In particular, rock abrasion by the crystalline radula of *Patella coerulea* while searching for food, together with dismantling and chemical dissolution by micro-organisms, other molluscs (*Littorina neritoides*) and echinoids (*Paracentrotus lividus),* which can tolerate high salt concentrations, is considered one of the causes of coastal erosion in the Adriatic. The mean erosion rates of rock (tab. 1), referring both to such organisms and to dissolution, differ. Regnauld (1995) attributes the formation

TABLE 1 - Removal rates of north Adriatic limestone substrate due to grazing and burrowing by gastropods and echinoids, and marine physicochemical dissolution (from Spencer, 1988, modified)

Agent	Rock erosion rate (mm/year)
Patella coerulea	0.51 ÷ 0.76
Littorina neritoides	0.07 ÷ 0.13
Paracentrotus lividus	1.1
dissolution	0.05 ÷ 0.25

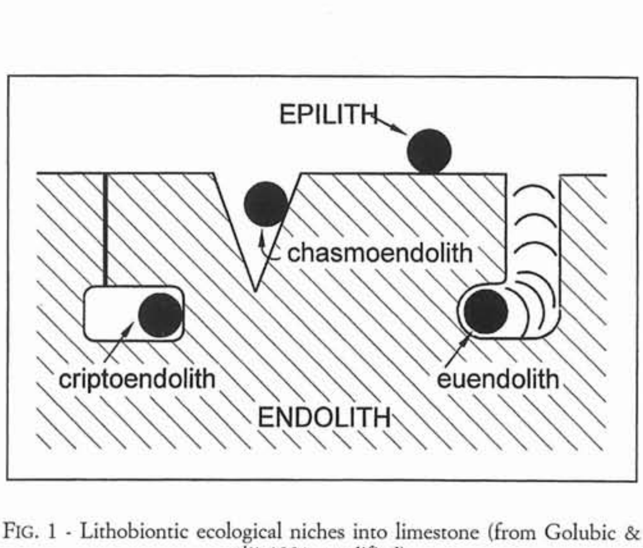

FIG. 1 - Lithobiontic ecological niches into limestone (from Golubic & *alii*, 1981, modified).

of rockpools along the limestone coasts of Ireland and Portugal to modelling by the sea, karstism and its inherited forms (*lapiéz*), as well as to cavities made by lithophages and echinoids. In the western Mediterranean, near *trottoirs*, mainly bioconstructed by the coralline alga *Lithophillum lichenoides* (Laborel & *alii*, 1994), basic conditions are established for the development of ephemeral decimetric rockpools (*micro-lagoons*), generally found at sea level and subparallel to the coastline, the elongated form of which recalls lagoonal environments on a small scale (fig. 2).

Many Authors have recorded the presence of rockpools on emerged and submerged marine abrasion platforms, found at various altitudes along Mediterranean coast cutting limestone (Brancaccio, 1968; Romano & Sgrosso, 1992; Donadio & *alii*, 1996; Ferrini & *alii*, 1996; Parroni & Silenzi, 1997; De Pippo & *alii*, 1998), pyroclastic rocks (De Alteriis & *alii*, 1996), lava basements (De Pippo & *alii*, 1996), metamorphic rocks (Orrù & *alii*, 1996) and beachrocks (De Muro, 1996).

Mention must also be made of the description of those forms, similar in aspect to rockpools, which occur along coastal cliffs in various places around the world, in both arid desert and cold regions, called *tafoni* and *alveoli* in Italian and *honeycombs* in English the last ones. Although these hollow subcircular forms, with diameters and depths ranging from a few centimetres to some metres, do have some morphological elements in common with rockpools, they mainly occur in pre-existing cavities on rocky surfaces of different lithology (e.g., arenite, tuff, ophiolite). Sunamura (1992) states that their genesis is linked to physicochemical rather than biological processes and, in particular, attributes an essential role in their formation to atmospheric phenomena which activate lithic disgregation by means of wind erosion, cryoclastism and thermoclastism, as well as rock dissolution in the spray zone outside the high tide level. The formation of honeycombs is closely linked to lithological structure, since those occurring along coastal cliffs are controlled by weak stratification joints. Instead, *tafoni* do not develop on horizontal surfaces like honeycombs and rockpools, but only on steep, vertical or reverse-gradient slopes (Sunamura, 1992). Rockpools very often coexist with *tafoni* and honeycombs, on which they sometimes are superimposed.

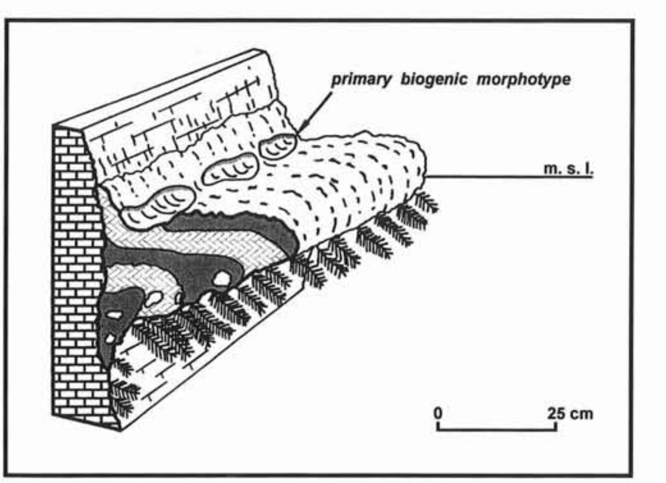

FIG. 2 - Structure of a *Lithophillum lichenoides* rim with micro-pools (from Laborel & *alii*, 1994, modified).

TYPES, FORMS AND ASSOCIATIONS

During surveys along emerged and submerged coasts in Campania (SW Italy: Sorrento Peninsula, Neapolitan coast, Phlegraean islands, Cilento coast), Latium (Central Italy: Circeo) and Apulia (SE Italy: Punta Pietre Nere, Gargano), thirteen main morphotypes were identified, classified into five categories, and attributed to differing genetic mechanisms and environmental conditions. It should be stressed that these forms may be found on any resistant substrate, and that they are circular or spindle-shaped in most cases. For the sake of simplicity, the macroscopic depressions forming in coastal environments on any rocky substrate with diameters between 0.1 and 1.0 m are called *rockpools*; forms with smaller or greater diameters are called respectively *micro-rockpools* and *macro-rockpools*.

The various types of rockpool may be distinguished according to the morphostructural situation of the landscape or seascape which contains them; in particular, bioconstructed forms may be distinguished from erosional ones, according to which of the two genetic factors prevails. For example, the former occur on *L. lichenoides* corniches along cliffs, whereas the latter are mainly found on marine abrasion terraces.

In order to compose a basic classification of the rockpools analysed here (fig. 3), reference was made, from the merely terminological viewpoint, to that of Castiglioni (1982) to describe the shape of karstic galleries and conduits. However, it should be emphasized that there is no direct genetic link between rockpools and karstic forms, although some of the former, in carbonatic lithologies, may sometimes develop in short subvertical karstic conduits (sinkholes).

The classification used here, based on rockpool geometry, necessarily uses terms which specify genesis and equality of shape (e.g., primary elliptical bioconstruction, structural elliptical superimposed, etc.). The I_p index (between 0.6 and 6) was also evaluated. This index is given by the ratio between rockpool diameter or length and mean depth, in order to interpret the evolutionary stage of the form and to identify its main controlling factor. With increasing I_p values, the structural conditions of the substrate containing the rockpool prevail over erosional phenomena. High values indicate evolution due to phenomena of piracy. In addition, rim and bottom characteristics, position and distance from the coastline, gradient and exposure to wave motion, altitude above sea level, lithology, direction of fractures, and dip of the strata have all been noted for each rockpool.

a) BIOGENIC FORMS

These forms are generally found on a substrate almost entirely built by animal and/or vegetal organisms, with

CATEGORY		MORPHOTYPE	GEOMETRY	SECTION	COAST SLANT	LITHOLOGY	ATTITUDE OF STRATA	I_p INDEX
	a) Biogenic	a1) primary			< 5°	biolith	subhorizontal	3 -:- 5
		a2) secondary			5° - 10°	any	subhorizontal	3 -:- 5
	b) Erosional	b1) pothole			20° - 40°	limestone sandstone conglomerate	subhorizontal sea-dipping	0.6 -:- 1
		b2) circular			< 45°	limestone sandstone conglomerate pyroclastite	subhorizontal sea-dipping	1 -:- 3
		b3) spindle-shaped			< 30°	limestone sandstone conglomerate pyroclastite	subhorizontal sea-dipping	3 -:- 5
	c) Superimposed	c1) elliptical			> 20°	limestone sandstone conglomerate (lava)	land-dipping (subhorizontal)	3 -:- 5
		c2) sinusoidal			< 45°	limestone sandstone	variable	1.5 -:- 6
		c3) on mark			< 45°	conglomerate breccia	variable	1 -:- 3
	d) Complex	d1) amoeboid			< 30°	limestone sandstone	subhorizontal sea-dipping	variable (> 2)
		d2) cluster			< 45°	limestone sandstone	variable	variable
		d3) comb-shaped			< 20°	limestone sandstone	cross-dipping	variable
	e) Artificial	e1) cylindrical			< 10°	any	subhorizontal	(1 -:- 3)
		e2) prismatic			< 10°	any	subhorizontal	(> 2)

FIG. 3 - Diagram of observed rockpools and coastal morphological and geological features.

subhorizontal dip and a gradient of less than 5°. As they are relatively shallow with respect to their size, their I_p index ranges between 3 and 5. In this case, two morphotypes were observed and, although they show some features in common, their genesis and morphology are different.

a1) *Primary*

To this morphotype belong oval or subelliptical micro-rockpools with major axes parallel to the coastline. In the Mediterranean, as already noted, they are common on rhodophytic corniches along rocky coasts, near the waterline. The shape and size of these rockpools are linked to the width of the bioconstructed rim and thus to the dynamics of the constructor organisms. These dynamics are in turn influenced by tidal range, erosion by wave motion related to coastal exposure, wind and insolation, as well as by the physico-chemical characteristics of seawater (Laborel & *alii*, 1994). *Micro-lagoons* are generally about 30 cm across and slightly above sea level (fig. 2).

a2) *Secondary*

These forms are found on sea terraces almost completely emerging from the water, in areas partially sheltered from wave motion. Their occurrence is due to the presence of small grooves or sills composed of molluscs (*Mytilus galloprovincialis*) and sometimes barnacles (*Balanus* sp.), generally living. These too are ephemeral micro- and macro-rockpools, the genesis of which is due to weak depressions in the colonized rocky substrate or previous eroded rockpools later filled in with shells. The shape, circular or irregular, also depends on the distribution of organisms, the geometry of the rocky cavity, and the size of the sill. Forms of this type, composed of mussel colonies on a marine abrasion platforms cut in Neapolitan yellow tuff, may be observed both along the western Neapolitan coast (Cala Trentaremi), and on lava platforms along the Vesuvian coast. They recall the much larger, flat-bottomed forms, rimmed by sills made by vermetid gastropods, which colonize similar platforms in Madagascar (Battistini, 1986).

b) Erosional forms

These are the result of chemical dissolution and mechanical erosion by both fresh and salt waters, and of the dismantling and corrosive activity of marine organisms. This category contains three main morphotypes, the last of which may be included among the erosional forms, even though its genesis appears to be different. The I_p index, varying between 0.6 and 5, falls in different intervals for each morphotype.

b1) *Pothole*

These are the result of the prevalent abrasion of the rock after vortex motion. Subcylindrical or hemispheric, they reach diameters and depths greater than 1 m and are often associated with one or more other potholes of similar shape and size. The I_p index ranges between 0.6 and 1, as sinking is predominant. Potholes, with perimetral grooves and slightly rounded pebbles on the bottom, generally form at heights of less than 2 m above sea level along coasts with gradients between 20° and 40° and well exposed to wave motion, mainly in areas typically subject to undertow. Those at Marina di Puolo (fig. 4a) on the Sorrento Peninsula are carved in weakly-sloping, flat, flint-bearing calcarenite and are all arranged along the same fracture, almost at right angles to the coast, with irregular perimetral grooves.

b2) *Circular*

These are the most common forms along Mediterranean coasts, frequently found in areas with gradients of less than 45°, on surfaces with subhorizontal or sea-dipping strata with lower inclination at a less acute angle with respect to that of the slope. The I_p index ranges between 1 and 3, since evolution is strongly controlled by substrate structure and gradient. They sometimes have a bottom with honeycombs and pinnacles, weakly convex (fig. 4b) or pipe-shaped (fig. 4c). There is very often a seaward gully, and almost at right angles to the coast. On the Mesozoic limestone of Marciano and Punta Lagno (Sorrento Peninsula), the rockpools decrease in density from 50 to 30 units/m^2 from the waterline inland (fig. 4d).

b3) *Spindle-shaped*

Commonly found in the belt near the beachline, generally larger than 0.2 m and with an I_p index of between 3 and 5, these forms may have a short wide gully, almost as wide as the pool itself, directed towards the coast or towards underlying rockpools according to the lines of maximum gradient (fig. 4e). In forms in limestone, as seen on the platform at Cape Sorrento, a subvertical sinkhole with a subhorizontal conduit (fig. 4f) may be present, debouching at the height of the sea notch. It thus appears that the genesis of these forms is controlled by the subhorizontal dip of strata, presence of fractures at right angles to the coast, and karstic phenomena. Spindle-shaped forms, although without karstic phenomena, have also been observed on the tuffaceous pavement of artificial cavities of Graeco-Roman age along the western Neapolitan coast (Grotta del Tuono, Cala Trentaremi).

c) Superimposed forms

These forms closely depend on the structure of the rocky substrate and the texture of the clasts composing it, particularly on layer dip and the presence and orientation of stratification joints, fracture planes and, in the case of conglomerates, the shape and size of pebbles. The I_p index varies between 1 and 6, due to evident structural control. Three morphotypes may be distinguished.

c1) *Elliptical*

This type is found on coasts with gradients exceeding 20° along interlayer planes with land-dipping strata and/or, less commonly, with sea-dipping strata. The I_p index generally ranges between 3 and 5 and the forms are oriented parallel to the coast. They also have vertices with acute angles and thin, irregular, perimetral grooves. Subelliptical forms are found at Marina di Puolo on the Sorrento Peninsula on land-dipping Mesozoic limestone strata (fig. 5a). Instead, some rockpools in the Punta Lagno limestone are superimposed on sea-dipping interlayer surfaces (fig. 5b). Similar forms also occur near Torre Mileto (western Gargano, Apulia), on a terrace cut in limestone with a seaward dip greater than the slope.

c2) *Sinusoidal*

This morphotype contains macro-rockpools overlying karstic structures, with *lapiéz* platform, or characteristic fracture systems. They may be found both parallel and transversal to the coast. In the former case, the sometimes intercommunicating rockpools have one or more continuous perimetral furrows at different heights, pebbles on the bottom, and well-rounded rims. In the latter case, they are mainly of structural type, following the fracture trend, and with rounded rims. These forms have an I_p index between

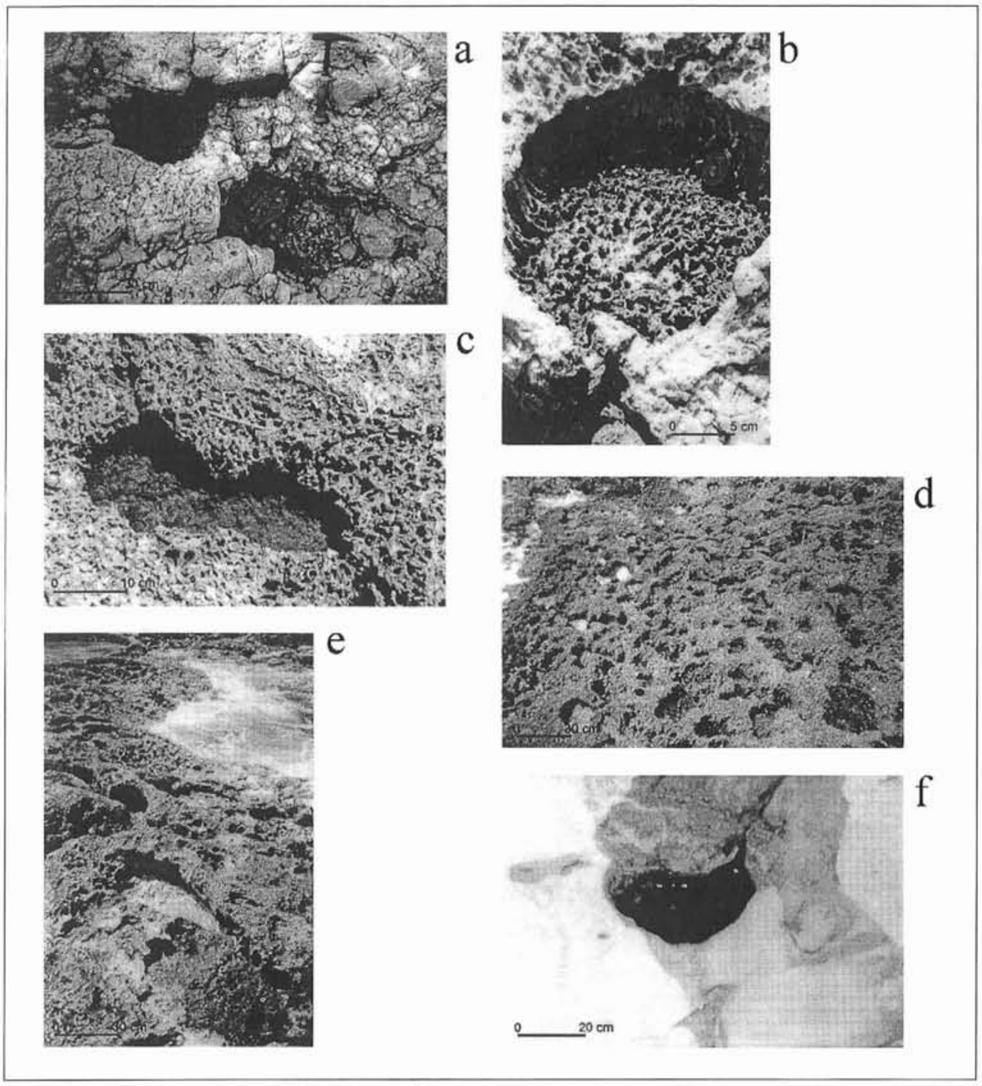

FIG. 4 - a) Potholes on calcarenitic coast at Marina di Puolo (Sorrento Peninsula, Southern Italy); b) micro-rockpool with bottom of a low convexity, honeycombs and a seaward gully; c) rockpool in centimetric pipe-shaped limestone; d) rockpools of decreasing density (from 50 to 30 units/m^2) from waterline to inland; e) spindle-shaped rockpool with seaward gully at right angles to coast; f) spindle-shaped rockpool on Cape Sorrento limestone, with a subvertical karstic sinkhole on bottom.

1.5 and 6. The forms observed in the limestone of Marciano (Sorrento Peninsula), from the waterline to about + 8 m above sea level, are about 6 m long and are arranged on a *lapiéz* pavement (fig. 5c). Instead, the structural sinusoidal rockpools along the Cape Sorrento coast are found on fractures in the limestone substrate running more or less parallel to the coast rather than transversally, because of the prevalent local orientation of the fracture system (fig. 5d).

c3) *Superimposed on mark*

These relatively rare forms arise in small cavities once occupied by pebbles or blocks removed or eroded from limestone conglomerates and breccias, or volcanoclastites, with a I_p index between 1 and 3. They inherit the form of the original clast and are generally subcircular and/or oval, although rectangular and trapezoidal forms are not lacking. Their average size is slightly greater than that of the former clasts (fig. 5e).

d) COMPLEX FORMS

These forms are the result of an association of several morphotypes, more or less similar, the origin of which is due to structural motifs, superimposing, piracy, or the interaction of several phenomena. Although sometimes occurring on fissured lava, they are extensively found on limestone rocks, preserving traces of their inherited morphology. Irregular shapes with acute angles may be generated at the intersection of fractures or in *lapiéz* cracks, whereas amoeboid forms derive from the capture of adjacent rockpools. One complex type often derives from the superimposing of forms of different generations or superimposing together with piracy on inherited karstic structures or fractured rocks. Sizes and I_p index values are extremely variable, due to the association of forms, in turn genetically controlled by several different morphostructural factors. They may be subdivided into three morphotypes.

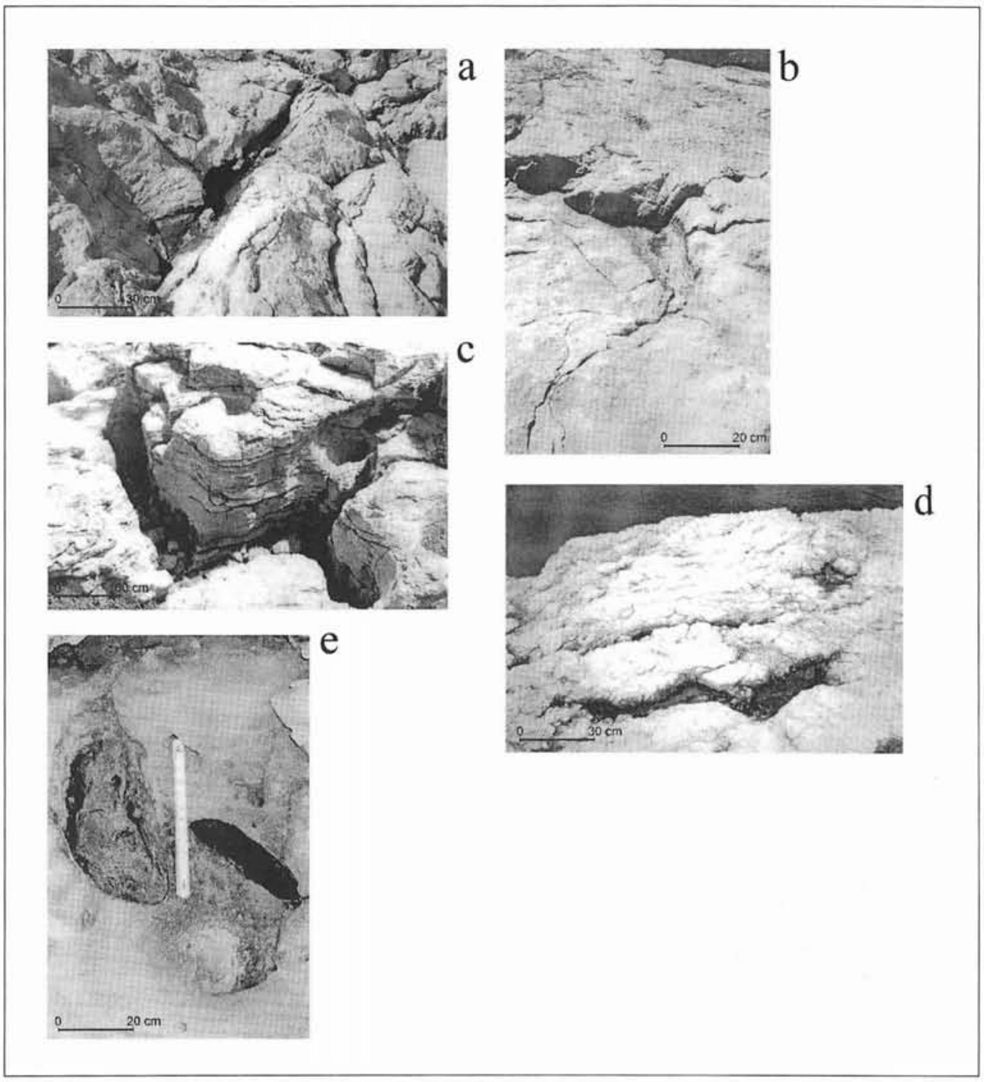

FIG. 5 - a) Rockpool superimposed on interlayer surface, land-dipping; b) rockpool superimposed on inter-layer surface, sea-dipping; c) sinusoidal rockpool superimposed on a *lapiéz* pavement; d) structural sinusoidal rockpool superimposed on a fracture; e) rockpool superimposed on a pebble-cast.

d1) *Amoeboid*

This form results from the evolution, by capture, of adjacent circular, spindle-shaped or sinusoidal rockpools. They may be generated either by the extension of pre-existing forms or by superimposing on intersecting fractures of various orientation (fig. 6a).

d2) *Cluster*

These morphotypes are generated along fractures almost at right angles to the coast, due to the superimposing of rockpools belonging to different generations, connected by intermediate channels or wide cuts. An example may be found at Punta Lagno on the Sorrento Peninsula (fig. 6b).

d3) *Comb-shaped*

This is an association of elliptical macro-rockpools extending subparallel, arranged almost at right angles to the coast and often intercommunicating. Examples are the large rockpools on the coastal platform of Punta Tresino (Cilento, Campania), resting on calcarenitic layers with cross-dipping strata.

e) ARTIFICIAL FORMS

Easily recognizable due to their extremely regular shape, these forms were mainly carved by man from Graeco-Roman times onwards, for various reasons. Their presence on flat surfaces near the sea is due to the suitable rocky substrate, the availability of water to work artefacts and, very probably, also to the possibility of transporting artefacts by sea. These forms may be subdivided into two morphotypes.

e1) *Cylindrical*

These forms are found as more or less regular cavities produced by the sometimes incomplete extraction of

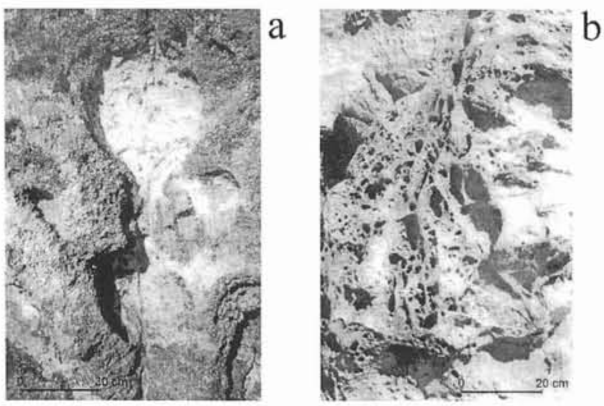

FIG. 6 - a) Amoeboid rockpool created by pyracy of adjacent spindle-shaped pools; b) cluster-shaped rockpools along a fracture.

blocks or as the holes originally made for wooden piles set in the rock. Artificial rockpools, although preserving their original shape, are quickly colonized by marine organisms and subjected to erosion. Some artificial circular rockpools (fig. 7a), about 80 cm in diameter and 20 cm deep, are reported on the eu-Tyrrhenian marine terrace at Lido Ficocelle (Cape Palinuro, Campania), and are the result of the extraction of cylindrical blocks for the *in situ* construction of a grindstone (Antonioli & *alii*, 1994, 1996). There are many subcylindrical artificial rockpools on the island of Ventotene (Latium), on a modelled emerging marine abrasion platform in the Pleistocene pyroclastic deposits of the area surrounding the Roman port (fig. 7d). These forms were carved in order to collect salt and probably also partially to attenuate wave motion (Limardo, 1989). One or more natural rockpools may sometimes be rendered artificial by anthropic changes, as in the singular case of the macro-rockpools at Punta Lagno (fig. 7b), where the seaward rim has been reconstructed, giving rise to a large subcylindrical form which constantly fills with water.

e2) *Prismatic*

These forms, frequent along the coasts of Campania and Latium, sometimes underwater and mainly on pyroclastic rocks, are due to the extraction of large blocks from marine abrasion platforms or coastal grottoes, used by the Romans for constructing *piscinae* and canals (fig. 7c). Some prismatic forms, excavated in Roman or perhaps Longobard times, are found at Lago, near San Marco di Castellabate, Salerno, along the Cilento coast.

MORPHOLOGICAL GENESIS AND EVOLUTION

Field observations clearly indicate that the genesis and development of rockpools, especially on limestone rocks, are due to several interacting processes and factors (Clark,

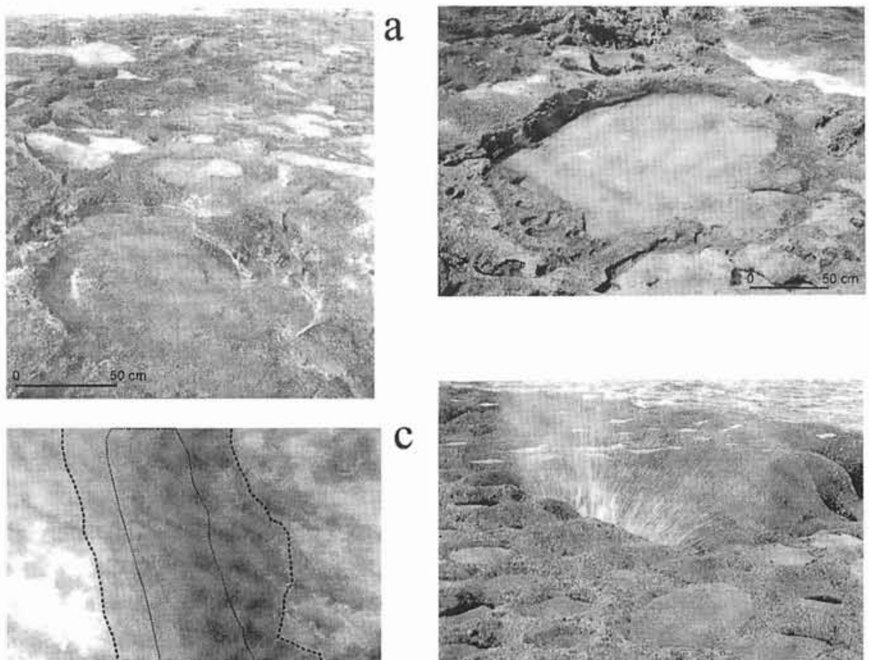

FIG. 7 - a) Artificial rockpool created by extraction of a cylindrical limestone block from a marine terrace of eu-Tyrrhenian age at Cape Palinuro (Campania, southern Italy), used to carve a grindstone *in situ* (from ANTONIOLI & *alii*, 1994); b) anthropically modified macro-rockpool at Punta Lagno (Sorrento Peninsula), showing captured forms on bottom; c) prismatic macro-rockpool carved during the Graeco-Roman period in a Neapolitan Yellow Tuff terrace (Campania, southern Italy), now submerged to 3 m depth due to bradyseismic phenomena (thick shaded line: rockpool rims; thin shaded line: rockpool bottom); d) artificial subcylindrical rockpools near Roman port on island of Ventotene (Latium, central Italy), carved in emerging surface of a pyroclastic marine terrace in order to collect salt and probably to reduce the wave action (from Limardo, 1989).

1977). Supporting previous knowledge in the Mediterranean, rockpools are normally found in the inter- and supratidal zones, between a few centimetres above sea level and the maximum reach of storm surges. Their presence is mainly caused by bio-erosion and biocorrosion by animal and vegetal marine macro- and micro-organisms, to the point at which we may speak of biokarstism (Spencer, 1988).

Rocks containing neo-rockpools are predisposed to mechanical dismantling by wave motion and exogenous agents. As a consequence of environmental conditions, to these processes must be added contemporary physico-chemical dissolving mechanisms which may prevail at various periods. The presence of submerged springs near the coastline also causes mixing between fresh and salt waters, giving rise to phenomena of hyperkarstism, with the rapid formation of cavities along tectonic discontinuities (Plummer, 1975; Lohmann, 1988; Forti, 1991).

Control of the mechanical and physico-chemical morphological action of exogenous agents (Parroni & Silenzi, 1977) is exerted by the differing resistance to erosion of the various outcropping rocks. While on one hand the precipitation of calcite in pores (Battistini, 1986) and the presence of encrusting superficial organisms (calcareous algae, vermetid gastropods, polychaetes, sponges) both slow erosion, on the other hand it is accelerated by specific abrasion (grazing) by the radula of certain gastropods (e.g., *Patella coerulea, Littorina neritoides*) and the spines and teeth of some echinoids (*Paracentrotus lividus)* in search of food and shelter. This biological activity is revealed by the typical small furrows and hemispheric niches in the rims of rockpools, especially in heavily colonized ones, along coasts particularly exposed to wave motion. Reduced density of rockpools in limestone, observed from the waterline inland, is linked both to the lesser spatial control exerted by physico-chemical and hydrodynamic factors and, obviously, to the lower numbers of marine organisms. The latter are selectively replaced by species more resistant to hyperhaline environments, when water turnover in rockpools is low (progressive drying-out), or hypohaline situations, when sea water occasionally mixes with rainwater.

In general, the distribution of sessile organisms colonizing rockpools gives the rocky surface of the coast different colours between the inter- and supratidal zones, gradually varying upwards from pale green to yellowish-brown, black, grey, and then white (Spencer, 1988). However, along the coasts examined in the present work, such colour zoning was not observed; on the contrary, in some cases, almost the reverse colours were found (fig. 4d), probably indicating the different distribution of the organisms (cyanobacteria, blue-green algae, halophytes, lichens). Although a greater variety of forms is found on limestone rocks, which are relatively resistant, very frequent along Mediterranean coasts, more extensively involved by fracture systems and easily exposed to the dissolving action of $CaCO_3$, rockpools also occur in other substrates at varying altitudes in both emerged and submerged environments.

The present study reveals the clear prevalence of circular and spindle-shaped types, as well as a general evolutionary trend towards these forms. These morphotypes generally do not form on coasts with gradients exceeding 45°, since meteoric and sea waters produce dissolution or run-off furrows on them: only at points with average or low gradients and on asperities or small rock fractures can subcylindrical micro-rockpools form on coasts well exposed to wave motion (fig. 8a) or subcircular forms if the coasts are less exposed (fig. 8b); these forms tend to increase in size over time. Instead, on sheltered coasts, sea spray generates honeycomb shapes on which circular forms are superimposed, sometimes with a cut in the seaward rim and an uneven, weakly convex bottom (fig. 4b).

On the basis of forms found *in situ* and those described by previous Authors, figure 9a shows the plan and cross-section of the gradual evolution of a pothole, in any resist-

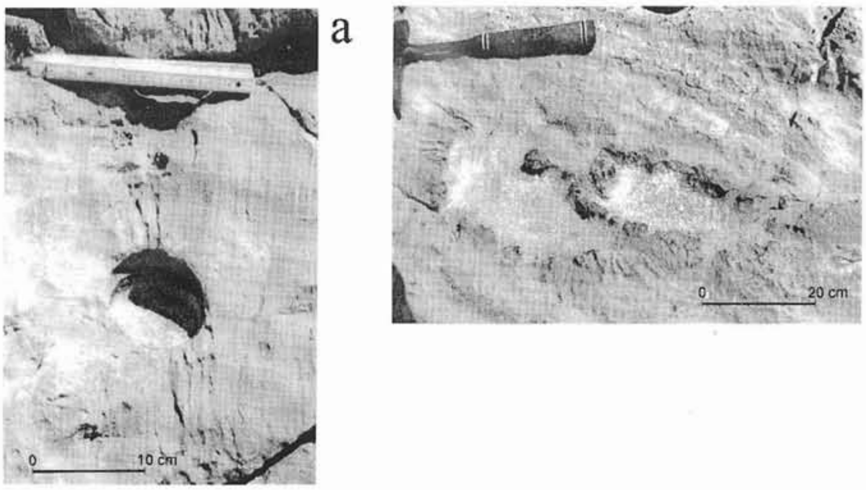

FIG. 8 - a) Cylindrical micro-rockpool developing on a wave-exposed limestone coast; b) sub-circular micro-rockpool developing in zone of a wave-sheltered limestone coast.

ant substrate. The pothole is created from a centimetric alveolus (a) and is initially widened and rapidly deepened (b) until it reaches equilibrium dimensions (c) as a result of hydrodynamic energy and mechanical, biological and chemical erosion. Sand (e) and pebbles (f) are deposited on the bottom, contributing to the formation of a hollowed rim as the result of vortex motion. Figure 9b shows the gradual development of a circular rockpool and its progressive transformation into a spindle shape. In this case, an alveolus or micro-rockpool (a) widens rapidly (b), and seaward erosion gradually prevails, with an increase in diameter (c, d, e) due to the entry of sea water during storms, finally creating a short gully (f), more or less at right angles to the coast, which later tends to become larger (g). Some limestone rockpools may evolve in short subvertical karstic conduits (sinkholes), especially near the waterline or on the edge of a terrace. In this case (fig. 9b), an already existing rockpool (e) tends to deepen into a funnel shape (i) and a narrow conduit sometimes forms on the bottom (cc). In the presence of sea-dipping strata or fractures at right angles to the coast, progressively in erosion (h), the subvertical circular conduit gradually assumes a subhorizontal trend among the joints, debouching near or just under the sea notch (sb), where excavation due to vortex motion may take place.

Clearly, pre-existing conditions necessary for the development of one or the other form are closely linked to the morphology and exposure of the coast to wave motion, climatic conditions, and the textural and structural features of the rocky substrate, as well as to complex competition among colonizing micro- and macro-organisms. In particular, potholes are more common on averagely steep coasts exposed to storms, composed of conglomerates in which erosion-resistant and easily moved clasts are available. However, it is possible to see similar forms, along pre-existing fractures at right angles to the coast, where vortexes form both during ascending and descending flows of sea water. If environmental conditions change for tectono-eustatic reasons, developing potholes generally evolve into circular or spindle-shaped rockpools, above all when they are close to the coastline. Evolved spindle-shaped forms, with marked, deep cuts at right angles to the coast, are frequent along the edges of marine abrasion terraces, e.g. the Sorrento Peninsula limestones, now sub-

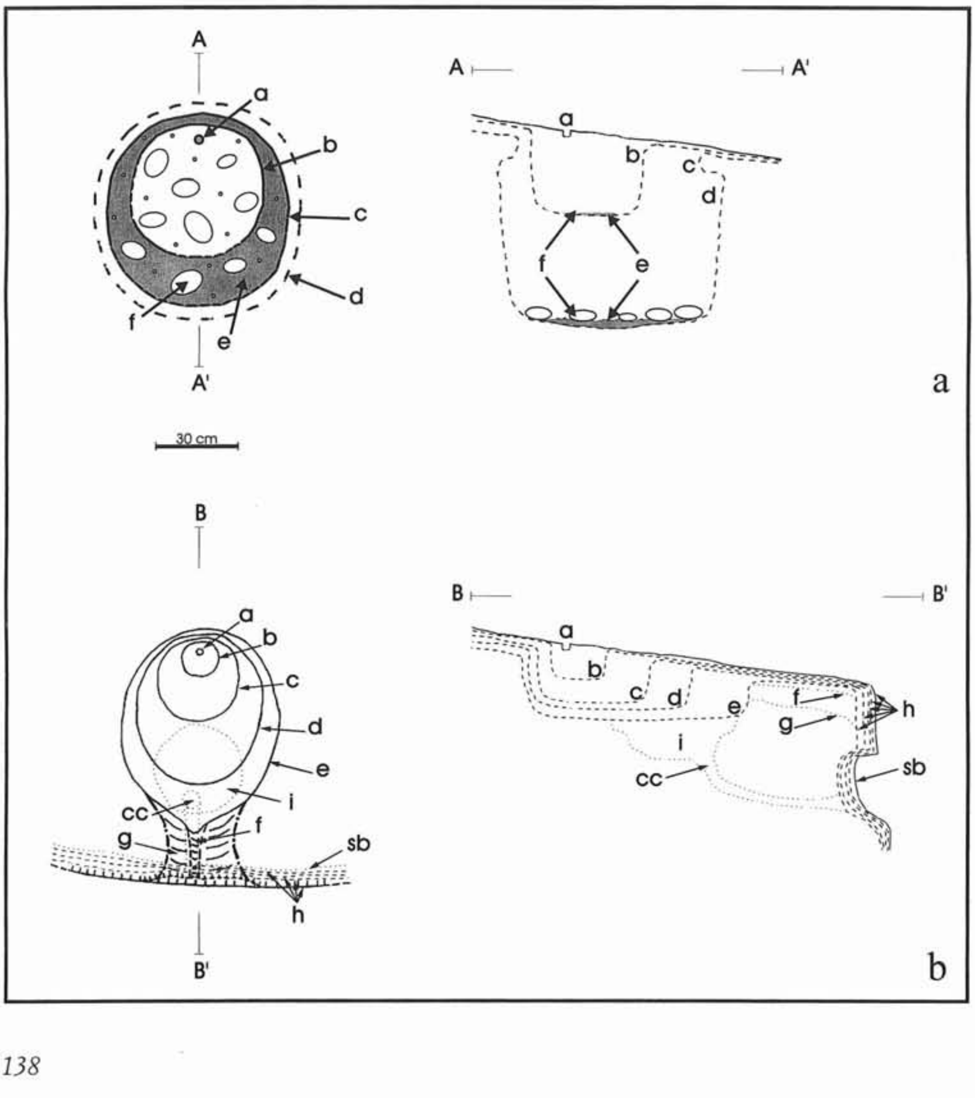

FIG. 9 - a) Plan and cross-section of evolutionary stages of a pothole; b) Plan and cross-section of evolutionary stages of a rockpool, from circular to spindle-shaped.

merged to various depths as a result of tectono-eustatic movements (fig. 10).

Many Authors observed potholes on resistant rocks such as conglomerates, limestone breccias, granite and ophiolite, whereas such forms on pyroclastic or effusive rocks do not appear to have been reported. In the case of pyroclastites, this is very probably due to their poor mechanical resistance, and to the fact that these lithologies do not commonly have shallow marine abrasion platforms. Moreover, potholes do not commonly develop in effusive rocks, due to the lack of flat outcropping erosional surfaces, to the way in which lava flows are emplaced in the sea, and to their particular resistance to erosion.

The time necessary for the formation and development of coastal potholes is very variable, due to the numerous biotic and abiotic factors involved, although a few dozen years may be hypothesized if the substrate rocks are averagely coherent. This time interval is probably longer than that indicated for the formation of giant potholes in fluvioglacial environments (Federici & Piacente, 1993).

Time estimates, although made with due caution, may be extrapolated from the exponential equation of Matsukura & Matsuoka (1991) for the *tafoni* of various ages and altitudes in the Miocene tuffaceous conglomerates of cliffs in Japan:

$$t = \frac{(20{,}3 - Dd) / 20{,}3}{0{,}005} \qquad [1]$$

Time t calculated for these forms, generated on a particular type of lithology in oceanic meteo-marine conditions, starting from the mean of the ten greatest depths D_d and desumed from the development of forms with an average depth of 6.5 cm in 66 years, allowed the above Authors to estimate a mean deepening rate of about 1.7 mm/year. This value is not very different from that calculated by Sunamura (1992) for the development of honeycombs on crystalline schists on the French Atlantic coast (1.1 mm/year); the value for forms on arenitic and volcanic blocks is about half (0.6 mm/year). In our case, according to equation [1] of Matsukura & Matsuoka (1991), circular rockpools 10 cm deep in limestone would take about 60 years to form, although this value must still be experimentally verified on various lithologies along Mediterranean coasts.

One frequently observed phenomenon is the capture of one or more rockpools by pirate forms, usually as a result of accelerated erosion along the outer rims of pools nearer the sea, generating complex forms. This phenomenon begins with the progressive expansion of adjacent forms and the opening of a gully which allows communication along the line of maximum gradient. When two or more rockpools coalesce, a new, irregularly shaped one develops, which tends to be subelliptical, with its major axis almost at right angles to the coast. Erosional processes then reduce the difference in depth of the pre-existing rockpools and amplify the gully, which is later obliterated. Piracy may extend to many adjacent rockpools and finally give rise to circular or spindle-shaped macro-rockpools with gullies debouching into the sea (figs. 4e and 6a). An example of this process is the macro-rockpool in the Punta Lagno limestone (Sorrento Peninsula), incorporating many minor forms, traces of which are visible on the bottom of the resulting form (fig. 7b).

Rockpools are not only found on present-day coastal platforms but also on ones which, as a result of tectono-eustatic phenomena, are now located both above and below current sea level. Forms above sea level are not always easy to identify, since subaerial erosion cancels elements distinguishing them from depressions caused by other phenomena such as karstism. On submerged abrasion terraces, erosion and chemico-physical dissolution model previous rockpools, generating complex types which occasionally reveal the earliest, original shape which developed in a tidal environment. Forms with features intermediate between circular rockpools and potholes may be observed in the limestone of the submerged marine abrasion platform at Marina della Lobra (Sorrento Peninsula), at a depth of about 1 m (fig. 11). These forms still have well-rounded

FIG. 10 - Evolved spindle-shaped rockpool, with large, deep gully, parallel to coast, located on a limestone marine terrace now submerged to 6 m depth by tectonic-eustatic events.

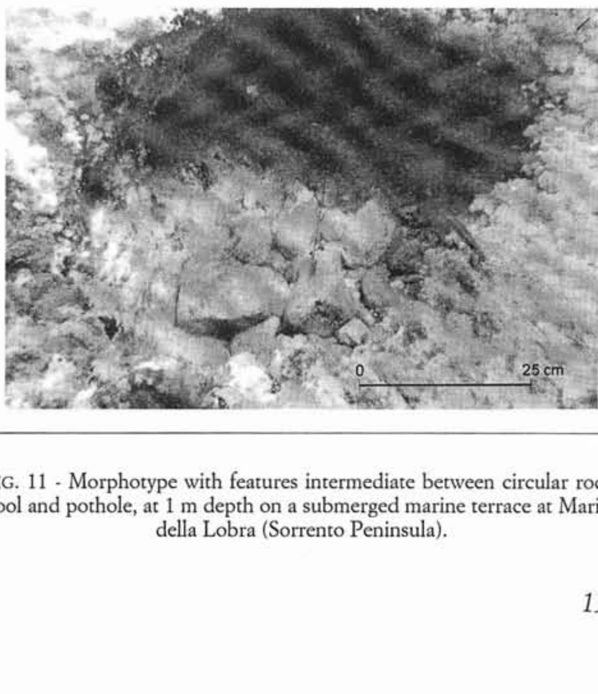

FIG. 11 - Morphotype with features intermediate between circular rockpool and pothole, at 1 m depth on a submerged marine terrace at Marina della Lobra (Sorrento Peninsula).

pebbles on the bottom but, unlike potholes, their rims are thin and sharp, with an I_p index of 1 or more. Here, probably originally circular rockpools, once submerged, were partly filled by clasts. Their different cross-section, wider at the bottom, is probably due to later modelling under water where, the energy necessary to form an emerged pothole being equal, vortex motion had a smaller erosional effect. Some potholes south of Scoglio Vetara (Li Galli, Sorrento Peninsula), in a limestone erosional surface 8 m deep, do not have the well-hollowed rim generally seen in coastal potholes. Here, they are large (diameter and depth exceeding 1 m), and contain rounded pebbles covered with encrusting organisms (fig. 12). It may be hypothesized that these potholes, once in an underwater environment, were subjected to erosion with amplification of their diameter and that, once at a certain depth, vortex motion strong enough to move the pebbles was not frequent.

On the limestone of the Punta Lagno abrasion surface, extending to a depth of about 3 m, there is a complex elliptical rockpool at about –1 m, on the flat bottom of which, centrally located along the axis of the pool, there is a second, deeper pool, subelliptical in shape (fig. 13). This complex type is probably the result of the submarine evolution of an originally subaerial elliptical or cluster form, lying on a fracture.

In areas with high sedimentation, rockpools may be rapidly buried and become «fossils». Examples are the circular forms found on the sea bottom at depths of about 8 m, on the Secca delle Formiche bank (Canale d'Ischia), modelled on hyaloclast deposits. These forms are filled with pyroclastic sand containing an abundant bioclastic fraction.

FIG. 13 - Complex elliptical morphotype on a submerged marine terrace at 3 m depth at Punta Lagno (Sorrento Peninsula), with a subelliptical macro-rockpool on flat bottom.

CONCLUSIONS

The present resarch identified thirteen morphotypes of rockpools, falling into five categories, together with some morphotypes with intermediate features. The various forms mainly occur on resistant rocks, in both emerged and submarine environments, but mainly on limestone, thanks to its ubiquity and frequent fracturing; circular forms are common, although there is a general evolutionary trend towards spindle-shaped ones.

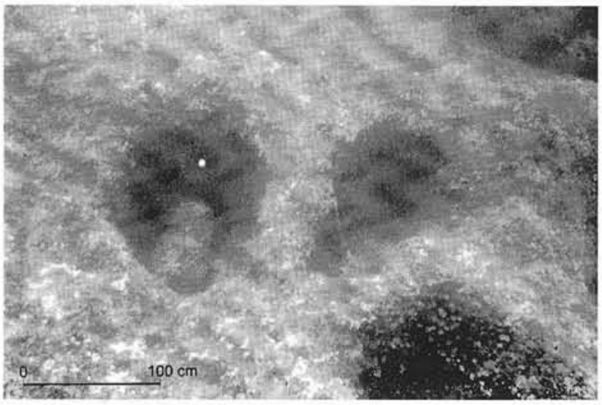

FIG. 12 - Large potholes with rounded pebbles on bottom at 8 m depth, south of Scoglio Vetara (Sorrento Peninsula).

In the genesis and evolution of the various forms described here, an important role is played by several environmental factors (climatic, biological, morphological) and their interactions. In particular, constant bio-erosion by marine micro- and macro-organisms in the inter- and supratidal zones in temperate climatic conditions, although contrasted by the action of bioconstructor organisms and salt precipitation, is probably responsible for the formation of rockpools, as also hypothesized by other Authors. To this action must be added contemporary chemico-physical erosion by both meteoric and sea waters, and mechanical erosion due to wave motion. The latter is also influenced by climatic conditions, the structural and textural characteristics of the rocky substrate, and coastal exposure.

It was observed that circular macroforms and potholes are generated mainly on coasts highly exposed to wave motion and with subhorizontal dip, or sea-dipping strata less inclined than the slope. These morphotypes may evolve into spindle-shaped forms after progressive amplification due to the ingression of sea water caused by slight tectono-eustatic movements, especially when the forms are located near the edges of abrasion terraces. Instead, the genesis of elliptical forms is controlled by land-dipping or cross-dipping strata; in the former case, rockpools also form on steeper coasts. Rockpools are not generally found on wave-exposed coasts with gradients exceeding 45°, tranversal gullies or micro-rockpools lying over *tafoni* and honeycombs more commonly form in their place.

On sheltered coasts, where chemical dissolution prevails, honeycomb belts develop, as well as circular micro- and macro-rockpools with uneven, weakly convex bottoms. In these morphotypes, frequent phenomena of piracy produce rejuvenated forms, generating complex and sometimes large rockpools.

Tectono-eustatic events, raising or lowering the marine abrasion surfaces containing rockpools, induce morphological variations, accelerate or slow their evolution, and generate «fossil» forms, relocating rockpools above the preceding sea level. Conversely, coastal sinking or sea level rises may remodel rockpools in submarine environments and, in certain cases, create «fossil» forms, either because such forms are located at depths exceeding 10 m or because they are filled with sediments. However, it is not always possible to distinguish whether these forms were generated during sea level highstands or lowstands, although the finding of well-preserved submerged forms up to depths of −20 m indicates that they formed during the most recent sea level rise.

REFERENCES

ANTONIOLI F., ASCIONE A., CINQUE A., FERRANTI L. & ROMANO P. (1994) - *Coastal and underwater geomorphology of Capo Palinuro area. Guidebook to the field - sea trip.* In: Guida all'escursione. Note scientifiche «Geosub 94», 8-10 Giugno 1994, Palinuro, De Frede, Napoli, 170 pp.

ANTONIOLI F., CINQUE A., FERRANTI L. & ROMANO P. (1996) - *Emerged and submerged quaternary marine terraces of Palinuro Cape (southern Italy).* Mem. Descr. Carta Geol. It., «Atti del Convegno Geosub 94», Palinuro, 8-10 giugno 1994, Serv. Geol. It., 52, 237-260.

BATTISTINI R. (1986) - *La morphogénese des plateformes de corrosion littorale dans les gres calcaires (plateforme supérieure et plateforme a vasques) et le probleme des vasques, d'apres des observations faites a Madagascar.* Mémoires de l'I.R.S.M., sér. F., t. 30, 81-94.

BRANCACCIO L. (1968) - *Genesi e caratteri delle forme costiere nella Penisola Sorrentina.* Boll. Soc. Natur. in Napoli, 77, 247-274.

CASTIGLIONI G.B. (1982) - *Geomorfologia.* Utet, Torino, 436 pp.

CLARK J.R. (1977) - *Coastal ecosystem management.* Wiley & Sons, NY, 928 pp.

DE ALTERIIS G, BRAVI S., DONADIO C. & FERRANTI L. (1996) - *Morfologie e strutture di apparati vulcanici sommersi nel Canale d'Ischia (Mar Tirreno).* Mem. Descr. Carta Geol. It., «Atti del Convegno Geosub 94», Palinuro, 8-10 Giugno 1994, Serv. Geol. It., 52, 85-96.

DE MURO S. (1996) - *Aspetti geomorfologici e cronologici di paleolinee di riva sommerse oloceniche nella piattaforma prossimale tra Capo Ferro e Capo Monti Russu (Sardegna nord-orientale, Italia).* Mem. Descr. Carta Geol. It., «Atti del Convegno Geosub 94», Palinuro, 8-10 Giugno 1994, Serv. Geol. It., 52, 309-322.

DE PIPPO T., DONADIO C., RUSSO F. & SGAMBATI D. (1996) - *Caratteristiche geomorfologiche del litorale vesuviano: evidenze per la ricostruzione della linea di costa di epoca romana.* Mem. Descr. Carta Geol. It., «Atti del Convegno Geosub 94», Palinuro, 8-10 Giugno 1994, Serv. Geol. It., 52, 207-224.

DE PIPPO T., DONADIO C. & SGROSSO A. (1998) - *Geomorfologia sottomarina di un settore della Penisola Sorrentina (Campania).* Geogr. Fis. Dinam. Quat., 21, 103-110.

DONADIO C., ROMANO P. & SGROSSO A. (1996) - *Ricerche di geomorfologia costiera in Penisola Sorrentina.* Mem. Descr. Carta Geol. It., «Atti del Convegno Geosub 94», Palinuro, 8-10 Giugno 1994, Serv. Geol. It., 52, 407-410.

FEDERICI P.R. & PIACENTE S. (1993) - *Geografia Fisica.* Nis, Roma, 400 pp.

FERRINI G, MENDICINO P. & TOCCACELI R.M. (1996) - *Caratteristiche morfostrutturali ed evoluzione recente dei fondali dell'Isola Dino (Calabria nordoccidentale, Italia).* Mem. Descr. Carta Geol. It., «Atti del Convegno Geosub 94», Palinuro, 8-10 Giugno 1994, Serv. Geol. It., 52, 135-148.

FORTI P. (1991) - *Processi ipercarsici e speleogenesi.* Speleologia, 24, 42-46.

GARNER H.F. (1974) - *The origin of landscapes. A synthesis of Geomorphology.* Oxford University Press, 734 pp.

GOLUBIC S., FRIEDMAN I. & SCHNEIDER J. (1981) - *The lithobiontic ecological niche, with special reference to microorganism.* Journ. Sedimentary Petrol., 51, 2, 475-478.

GUILCHER A. & JOLY F. (1954) - *Recherches sur la morphologie de la côte atlantique du Maroc.* Trav. Inst. Scient. Chérifien, sér. géol. et géogr. phys., 2, 140 pp.

GUILCHER A., BERTHOIS L. & BATTISTINI R. (1962) - *Formes de corrosion littorale dans les roches volcaniques, particulièrement à Madagascar et au Cap Vert (Sénégal).* Cahiers Océanogr., XIVème année, 4.

ISSEL R. (1918) - *Vita latente per concentrazione delle acque (anabiosi osmica) e biologia delle pozze di scogliera.* Mitteilungen a.d. Zool. Station zu Neapel, 7, 22 pp.

LABOREL J., MORHANGE C., LAFONT R., LE CAMPION J., LABOREL-DEGUEN F. & SARTORETTO S. (1994) - *Biological evidences of sea-level rise during the last 4500 years on the rocky coasts of continental southwestern France and Corsica.* Int. Journ. Marine Geol. Geochem. Geoph., 120, 203-223.

LIMARDO R. (1989) - *L'isola dell'Impero.* In: AQVA, 35, Maggio 1989, 73-79.

LOHMANN, K.C. (1988) - *Geochemical patterns of meteoric diagenetic system.* James N.P. & Choquette P.W. Eds., Paleokarst Springer-Verlag, 58-80.

MATSUKURA Y. & MATSUOKA N. (1991) - *Rates of tafoni weathering on uplifted shore platforms in Nojima-zaki, Boso Peninsula, Japan.* Earth Surf. Proc. Landforms, 16, 51-6.

ORRÙ P., COCCO A. & PANIZZA V. (1996) - *Rilevamento geomorfologico subacqueo del settore compreso tra Capo Boi e Punta Is Cappuccinus (Sardegna sud-orientale).* Mem. Descr. Carta Geol. It., «Atti del Convegno Geosub 94», Palinuro, 8-10 Giugno 1994, Serv. Geol. It., 52, 163-176.

PARRONI F. & SILENZI S. (1997) - *Paleoeustatismo e geomorfologia nel settore costiero emerso e sommerso di Marina di Novaglie (LE).* Boll. Soc. Geol. It., 116, 421-433.

PLUMMER L.N. (1975) - *Mixing of seawater with calcium carbonate groundwater.* Quantitative studies in geological sciences, Geol. Soc. Am. Mem., 142, 219-323.

REGNAULD H. (1995) - *Gèomorphologie et forme du littoral.* Le Paysage Littoral, Ecole Régionale des Beaux-Arts de Rennes, Presses Univ. de Rennes, 3, 86-91.

ROMANO P. & SGROSSO A. (1992) - *L'evoluzione geomorfologica della grotta subacquea dell'Isca (Penisola Sorrentina Campania).* Giorn. Geol., ser. 3, 54/2, 151-163.

SPENCER T. (1988) - *Limestone coastal morphology: the biological contribution.* Progr. Phys. Geogr., 12, 66-89.

SUNAMURA T. (1992) - *Geomorphology of Rocky Coasts.* Wiley & Sons, UK, 277 pp.