

Lower Pliocene (Zanclean) regressive sequence of Rafina near Pikermi in Attica, Greece: A spectacular locality of mass-aggregated giant balanid cirripedes*

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ABSTRACT: Sedimentological and eco-taphonomic attributes of the Lower Pliocene (Zanclean) regressive sequence exposed at Rafina Cliff near Pikermi in Attica, Greece, are analyzed in terms of their bearing on environmental conditions under which the large- to giant-sized balanid cirripedes *Concavus (Concavus) concavus* (DARWIN, 1854) [*non* BRONN, 1831] have profusely lived and become buried either scatterly through the sequence, or mass-aggregated in one, spectacularly structured bed of the *Fossilagerstätte* type. All balanids, regardless of their solitary or clustered lifestyle, are post-mortem transported, abraded and/or bioeroded, and deposited in offshore tempestites during high-stand pulses. The burrows of the callianassid shrimp *Upogebia*, and of the ghost crab *Ocyrops*, indicate short-termed, extremely shallow sub- to intertidal low-stand pulses. The whole sequence, being the uppermost part of the ‘post-Pikermian’, Lower Pliocene (Zanclean) marine overflood, is composed of three, successively thinning, shallowing-up cyclothems, topped by sub- to intertidal and/or emersive episodes, the last of which is featured by beachrock horizons that terminate the regressive events preceding an encroachment of the potamogenic (fluvial and/or deltaic) regime.

Key-words: *Regressive cyclothems, Balanid cirripedes, Eco-taphonomy, Burrows, Mass burial, Fossilagerstätte, Pliocene, Greece.*

ΠΕΡΙΛΗΨΗ: Τα ιζηματολογικά και οικο-ταφονομικά χαρακτηριστικά της οπισθοδρομικής ακολουθίας, ηλικίας Κατώτερο Πλειόκαινο (Ζάγκλινο), η οποία εκτίθεται στο βράχο της Ραφήνας, κοντά στο Πικέρμι Αττικής, Ελλάδα, αναλύονται σε σχέση ως προς τις περιβαλλοντικές συνθήκες οι οποίες ευνόησαν το μεγάλο έως γιγάντιου μεγέθους θυσανόποδο *Concavus (Concavus) concavus* (DARWIN, 1854) [*non* BRONN, 1831] να ζήσει σε μεγάλη αφθονία και να θαφτεί διάσπαρτα στα ιζήματα της ακολουθίας, ή να δημιουργήσει μια μαζική συγκέντρωση σε ένα στρώμα με χαρακτηριστική δομή του τύπου *Fossilagerstätte*. Όλα τα balanids, ανεξάρτητα από τον μεμονωμένο ή συγκεντρωμένο τρόπο ζωής τους, έχουν υποστεί μεταθανάτια μεταφορά, τριβή και/ή βιοδιάβρωση, και έχουν αποθεθεί σε ανοιχτές θάλασσες τεμπεστίτες κατά τη διάρκεια παλμικής ανόδου της θάλασσας. Η εμφάνιση βιοδηλωτικών ιχνών των αρθρόποδων *Upogebia*, και *Ocyrops*, υποδηλώνουν μικρής διάρκειας, υπο- έως ενδοπαλιροαικές παλμικές κινήσεις της θάλασσας. Ολόκληρη η ακολουθία, της οποίας το ανώτερο τμήμα αντιπροσωπεύει μια θαλάσσια πλημμύρα που έλαβε χώρα κατά το Κατώτερο Πλειόκαινο (Ζάγκλινο), αποτελείται από τρία κυκλοθέματα, τα οποία διαδοχικά γίνονται λεπτομερέστερα ως προς το πάχος τους και το μέγεθος των κόκκων τους, τα οποία καλύπτονται στην οροφή από υπο- και/ή ενδοπαλιροαικά επεισόδια ή επεισόδια ανάδυσης της θάλασσας τα οποία χαρακτηρίζονται από ψηφιδωπαγή που ουσιαστικά τεματίζουν τα επεισόδια ανάδυσης.

Λέξεις-κλειδιά: οπισθοδρομικά κυκλοθέματα, θυσανόποδα, Οικο-ταφονομία, βιοδηλωτικά ίχνη, μαζικός ενταφιασμός, *Fossilagerstätte*, Πλειόκαινο, Ελλάδα.

INTRODUCTION

The scope of this paper is to describe the poorly studied Lower Pliocene (Zanclean) sequence of Rafina near the classical Geosite Pikermi in Attica, some 27 kms NE of Athens, Greece (Fig. 1). The area yields a spectacular location of mass-aggregated, large-sized (‘giant’) balanid cirripedes classified recently (RADWAŃSKA & RADWAŃSKI, 2008) as *Concavus (Concavus) concavus* (DARWIN, 1854) [*non* BRONN, 1831].

This spectacular location in the small town of Rafina (spelled also *Raphena*; from Greek Ραφήνα, pronounced as *Rah-fee-nah*) is a cliff exposure spreading along the picturesque shores of the Rafina Bay, Aegean Sea (Fig.

2A-B). The balanid-bearing sequence, exposed along a distance of over 300 meters, and dipping slightly (7-8°) southward, has attracted a common attention since its first description by MITZOPOULOS (1948). All subsequent reports characterize it briefly as a sandy sequence that bears marine fossils, and thus contrasted with unfossiliferous sequences located both beneath (the ‘Pikermi Loams’) and above (continental gravelstones and travertines), as presented by GUERNET & SAUVAGE (1970, fig. 1), SYMEONIDIS & MARCOPOULOU-DIACANTONI (1977, fig. 11), GEORGIADIS-DIKEOULIA *et al.*, (1979, fig. 1), and MARCOPOULOU-DIACANTONI *et al.*, (1998, fig. 2).

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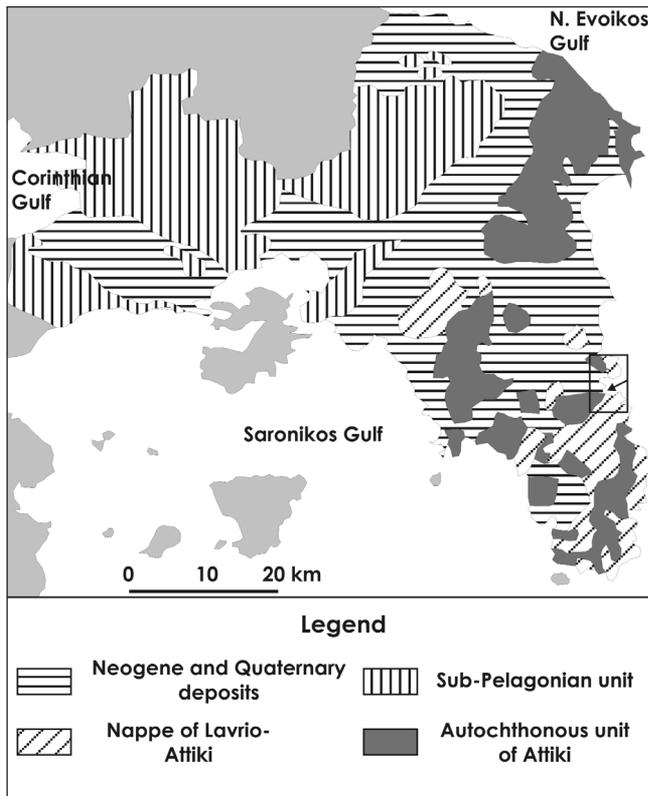


Fig. 1. Geological map of the Attiki peninsula indicating the location of the Lower Pliocene (Zanclean) balanid-bearing regressive sequence at Rafina near Pikermi in Attiki, Greece.

The original study of the Rafina fossils, performed by MITZOPOULOS (1948), concerned the lower (transgressive) part of the marine Lower Pliocene (Zanclean) sequence, then exposed at Rafina Harbour, but nowadays inaccessible. The list of fossils, presented by MITZOPOULOS (1948, p. 297) contains as many as 52 species (2 balanids, 14 gastropods, 19 scallops, 4 oysters, 12 other bivalves, and 1 brachiopod). The presently exposed, uppermost (regressive) part of the sequence at Rafina Cliff yields dominantly the balanids and a minor amount of calcite-shelled bivalves (isolated valves of scallops and oysters), the other calcite-shelled fossils having been extremely rare, and all aragonite-shelled ones having been leached out.

Concerning the balanids, MITZOPOULOS (1948) reported the presence of “*Balanus concavus* BRONN” and “*B. tulipiformis* ELLIS” without any information on their frequency. The mass occurrence was first indicated by SYMEONIDIS & MARCOPOULOU-DIACANTONI (1977, p. 115), and soon after pointed out by GEORGIADES-DIKEOULIA *et al.* (1979, p. 28), what involved a common fame of this locality to yield ‘giant’ barnacles, and to form a *Fossilagerstätte* becoming a bonanza for amateur collectors, students, and participants of several scientific field sessions.

A separate study of mass-aggregated balanids of the Rafina Cliff, their morphology and integrated eco-

taphonomy (RADWAŃSKA & RADWAŃSKI, 2008) has recently revealed that the whole hitherto recognized material is monospecific, represented exclusively by one species, *Concavus (Concavus) concavus* (DARWIN, 1854) [*non* BRONN, 1831], typified by a very broad range of morphologic variables and differing in its mode of growth, either solitary or clustered. The peculiarly shaped forms, having been classified as separate taxa in the literature, are nothing else but ecophenotypes of this species. As a result, it has been indicated that the Rafina balanids evidence the occurrence of only one species, instead of two (listed by MITZOPOULOS, 1948), or even ten, as distinguished by MARCOPOULOU-DIACANTONI *et al.* (1998).

Subjected to this paper is thus an analysis of the development of the balanid-bearing part of the sequence, and of environmental conditions under which the balanids have profusely lived to dominate over other biota.

GEOLOGICAL SETTING

Rafina Cliff is located in the Attiki peninsula. The area of Attiki forms part of the Attic–Cycladic belt, which belongs to the central Hellenides and is composed of a stacked sequence of nappes mainly emplaced in the Early Eocene (DÜRR *et al.*, 1978).

The geological structure of the broader area is dominated by alpine and post-alpine formations (Fig. 1). The alpine formations belong to three main stratigraphic units, the sub-Pelagonian unit, the autochthonous unit of Attiki and the nappe of Lavrio-Attiki. The sub-Pelagonian unit is composed of clastic formations (arkose, greywacke, phyllite, sandstone, and schist), limestones, dolomites, ophiolitic formations, transgression limestone, iron manganese ores and flysch. The autochthonous unit of Attiki comprises mainly schists, marbles and limestones, while the nappe of Lavrio-Attiki consists of phyllite, schist and metalliferous ores. The Neogene deposits consist of marls, clays, sandstone, conglomerates and travertine limestone. Pleistocene continental deposits and Holocene deposits include unconsolidated material with sand and pebbles, alluvial sediments debris cones and lateral deposits (LEPSIUS, 1893; MARINOS & PETRASCHKE, 1956; KATSIKATSOS *et al.*, 1976; GAITANAKIS, 1982; JACOBSHAGEN, 1986; KATSIKATSOS *et al.*, 1986).

The plain in the eastern part of the Attiki peninsula constitutes up to 700 m of reddish terrestrial, mostly coarse clastic sediments (correlated regionally with the Pikermian mammalian fauna) overlain by fresh-water marl, carbonates, travertine and minor lignite. Pikermi hosts a unique and well documented mammal fauna which contains micro- and macro-mammals (faunal lists in SYMEONIDIS *et al.*, 1973; DE BRUIJN, 1976; RÜMKE, 1976; BERNOR *et al.*, 1996; DE BRUIJN *et al.*, 1999). The association was named “Pikermian” by CRUSAFONT & VILLALTA (1954), which later was replaced, by the

“Turolian” (CRUSAFONT, 1965). The occurrence of the rich Late Miocene mammal fauna of Pikermi, has been related to seasonal evaporation in a paleo-lake basin associated with the Messinian salinity crisis (BACHMAYER *et al.*, 1982).

Along the east coast of the Attiki peninsula, the Pikermian beds pass into or are unconformably overlain by up to 80 m of fluvial conglomerates at Rafina (METTOS, 1992). These conglomerates pass laterally into, or are overlain by, a marine Pliocene succession. Similar successions up to 50 m thick outcrop in places all along the eastern coast of the Attiki peninsula, unconformably overlying Pikermian strata or alpine basement rocks.

The marine Pliocene succession has been dated from the lower part of the middle Pliocene by MITZOPOULOS (1948) and CHRISTODOULOU (1961). According to MITZOPOULOS (1948) this part of the succession encloses a very rich fauna of invertebrates, such as *Pecten reghiensis*, *P. benedictus*, *P. jacobaeus*, *Chlamys opercularis*, *Ch. varia*, *Ch. multistriata*, *Ch. flexuosa*, *Ch. inaequicoslalis*, *Ch. glabra*, *Ch. scabrella*, *Ch. bollenensis*, *Ch. pespfelis*, *Flabellipecten bosniasckii*, *Fl. flabelliformis*, *Fl. alessi*, *Fl. nigromagnus*, *Amussium cristatum*, *Cardium edule*, *Hinnites crispus*, *Spondylus gaederopus*, *S. crassicosta*, *Ostrea edulis*, *O. cochlear*, *Anomia ephippium*, *Lima inflata*, *Terebratulina ampula* all characteristic for the Pliocene.

In the same interval, CHRISTODOULOU (1961) determined a rich benthic foraminifera microfauna which comprises Nonionidae, Rotalidae, Buliminidae, Anomaliniidae and Amphisteginidae, all indicative of a very shallow marine environment. Unfortunately the micropaleontological analysis did not yield planktonic foraminifera or calcareous nannofossils.

THE RAFINA SECTION

The section of the Rafina Cliff (7 m thick) is mainly composed of conglomerates, silty to fine-grained sands and coarse sandstones. In Fig. 3 the lithostratigraphical column together with the lithofacies analysis and the paleoenvironmental interpretation are shown. Overall 15 beds have been distinguished.

Bed No. 1 – Poorly stratified silty sand; no fossils.

Bed No. 2 – Conglomeratic horizon: oyster and scallop valves, limestone pebbles and/or cobbles bored by rock-boring bivalves, rare balanid shells.

Bed No. 3 – Indistinctly stratified silty sand.

Bed No. 4 – Stratified sand, with shell debris: large scallop valves (at the base), small scallop, oyster, and not uncommon balanid shells (at the middle, upon scallop valves, see Fig. 7); silty inliers at the top.

Bed No. 5 – Silty sand, heavily bioturbated: small-sized burrows filled with non-contrasting sand, and diffused by irregular cementation.

Bed No. 6 – Distinct burrow-bearing horizon in

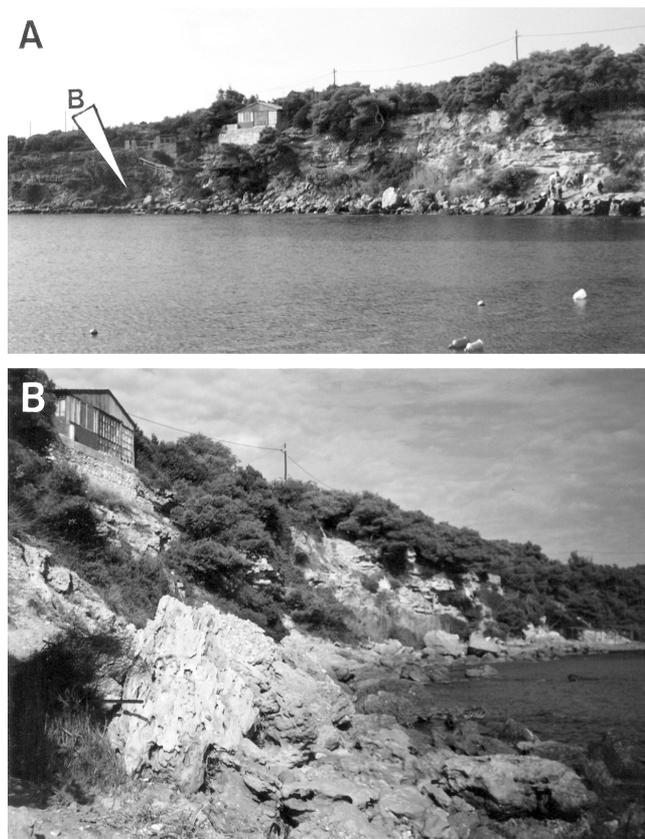


Fig. 2. A – General view of exposures of the Lower Pliocene (Zanclean) regressive sequence in the Rafina Bay, Attiki, Greece; photo by Michalis D. Dermitzakis, B – Close-up at Rafina Cliff, to show a part of the sequence (arrowed in Fig. A) the best exposed for field studies (see section, Fig. 3; and RADWAŃSKA & RADWAŃSKI, 2008, fig. 2A-B); photo by Michalis D. Dermitzakis.

loose silt: burrows irregularly cemented, and some cementations propagated from the burrows; most of the burrows belonging to the callianassid shrimp *Upogebia* are truncated at their tops.

Bed No. 7 – Bioturbated, compact sandstone, burrowed at the base, with balanid shells accumulated heap-like locally.

Bed No. 8 – Irregular bed of indistinctly stratified silty sand with scattered balanid shells.

Bed No. 9 – The main balanid-bearing sandy bed (9a), replete with large- to giant sized shells of *Concavus (Concavus) concavus* (DARWIN, 1854) [*non* BRONN, 1831], either solitary or clustered (see Figs 4-5; and RADWAŃSKA & RADWAŃSKI 2008), with scallop valves and rare oysters, both overgrown heavily by balanids (see Fig. 8); grading upwards (9b) into finely-stratified silty sand with shell debris (shellgrit), primarily of scallop valves and balanid opercular valves, scuta in particular.

Bed No. 10 – Silty sand, with aggregated scallop valves and their hash, larger-sized oyster (and/or thorny-oyster) valves, some of which are bored by rock-boring bivalves; balanid debris rare.

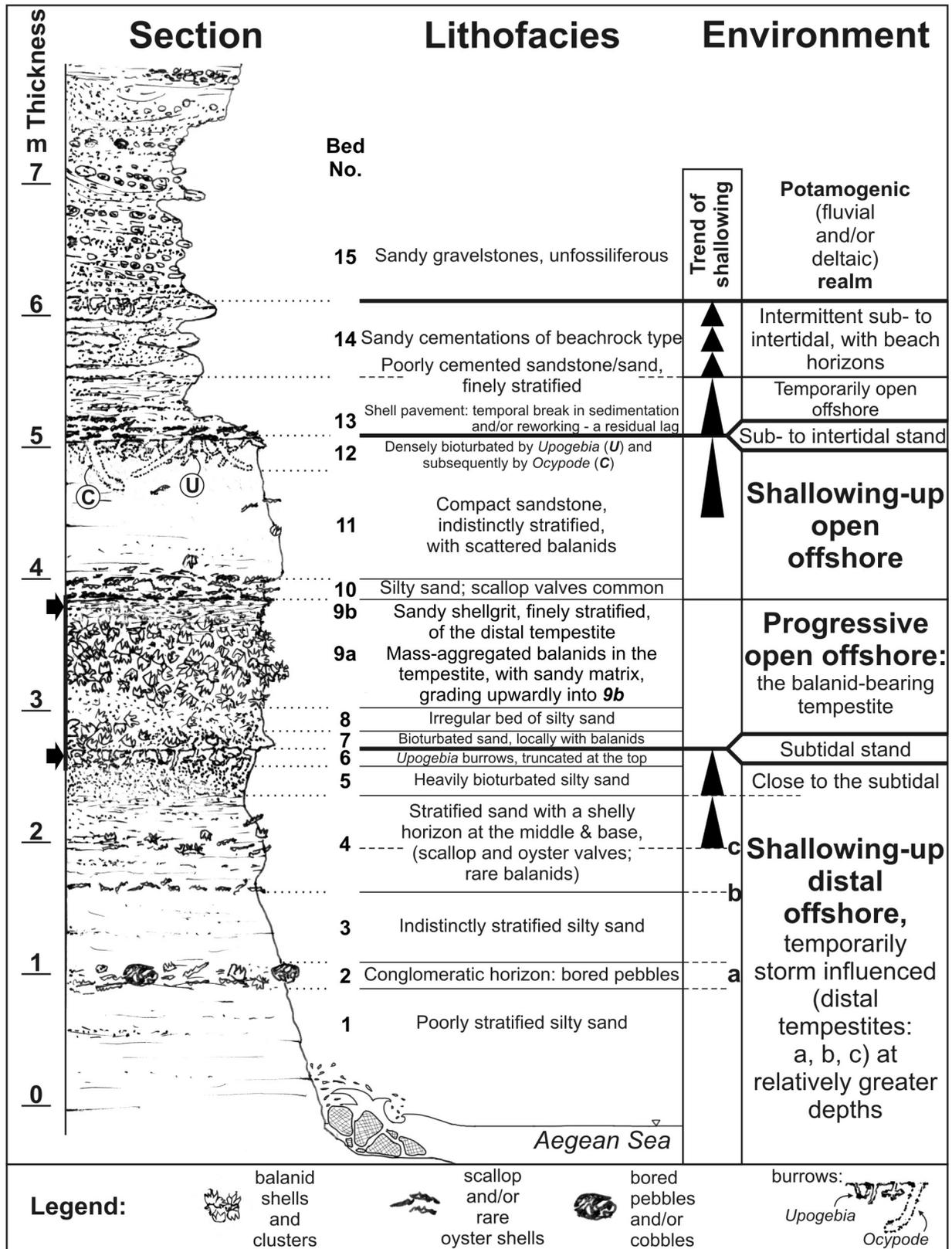


Fig. 3. Rafina Cliff section, to show the anatomy of lithofacies and their environmental interpretation; arrowed is a part detailly studied by RADWAŃSKA & RADWAŃSKI (2008, fig. 3).

Bed No. 11 – Compact sandstone, indistinctly stratified, with scattered balanids and scallop valves.

Bed No. 12 – Distinct burrow-bearing horizon in sandstone: burrows of two generations, the older ones, produced by the callianassid shrimp *Upogebia*, are transected by those produced by the ghost crab *Ocyrodes*.

Bed No. 13 – Sandy gravelstone, with a shell pavement (scallops, oysters) over the burrow maze of Bed No. 12; balanids scattered irregularly.

Bed No. 14 – Fine-grained sand with extensive, lenticular, or flattened loaf-shaped cementations of beachrock type; shell debris accumulated locally; indistinct *Upogebia* burrows at the top.

Bed No. 15 – Coarse-grained sandy gravelstone with exotic material: this is the base (up to 5 metres thick) of the 'Lower Conglomerate' of previous authors (SYMEONIDIS & MARCOPOULOU-DIACANTONI, 1977, p. 115; MARCOPOULOU-DIACANTONI *et al.*, 1979, p. 28), locally of horizontal and large-scale trough stratification; marine fossils absent.

The balanids occur in varied frequencies in almost all beds from No. 2 through 14, having been accumulated in some of them (Beds No. 4 and 7), to become mass-aggregated, rock-building components in Bed No. 9, the material of which has recently subjected to a separate eco-taphonomic study (RADWAŃSKA & RADWAŃSKI, 2008).

THE BODY AND TRACE FOSSILS

In the section at Rafina Cliff, apart from the balanids and taxonomically unrecognizable diverse scallops, and sporadic oyster valves, there also appear remains of some body fossils, as well as traces of their life activity (borings of rock-borers, gnawing of grazers, burrows), poorly or not hitherto reported from the Rafina sequence.

Body fossils

The list of taxa presented by MITZOPOULOS (1948) is enlarged by the occurrence of:

- the tube-dwelling polychaete *Ditrupa arietina* (O.F. MÜLLER, 1776),
- the gastropod *Xenophora* sp.,
- the regular echinoid *Cidaris desmoulini* SISMONDA, 1842.

The remains of these taxa are briefly accounted as follows.

The commonly occurring tube-dwelling polychaetes represent the species labeled traditionally as *Ditrupa cornea* (LINNAEUS, 1767), and widely reported from the Paleocene-to-Pliocene sequences of Europe, as well as from the present-day shores of the Atlantic and Mediterranean (see RADWAŃSKA, 1994, pp. 62-63). As revised by BIANCHI (1981, pp. 123-125), however, the only species that lives today in the Mediterranean is *Ditrupa*

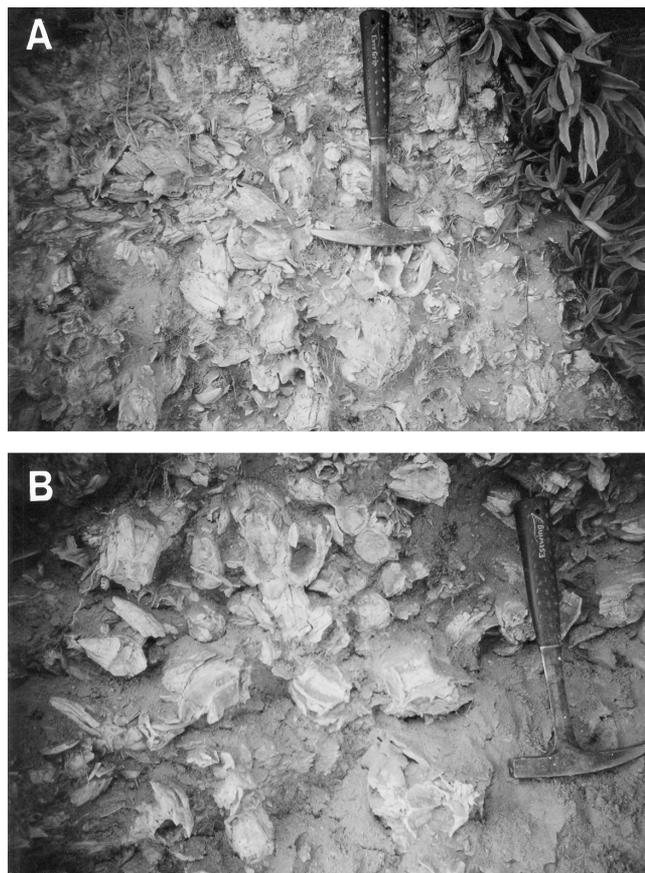


Fig. 4. A – Aggregation of clusters of giant balanids *Concavus (Concavus) concavus* (DARWIN, 1854), isolated shells and their hash, in the middle part of Bed No. 9a (section view) of the Rafina Cliff section, B – Aggregation of larger clusters of giant balanids *Concavus (Concavus) concavus* (DARWIN, 1854) in another part of Bed No. 9a of the Rafina Cliff section.

arietina (O.F. MÜLLER, 1776). Moreover, TEN HOVE & SMITH (1990, p. 101) objected the validity of the Linnean holotype of *D. cornea* and all former reports of this species, and suggested that the only, really existing species in the present-day Atlantic-Mediterranean bioprovince is just *Ditrupa arietina* (O.F. MÜLLER, 1776). Under this name the species was reported from the Pliocene and Pleistocene of Italy (as affinis, TEN HOVE & SMITH, 1990, p. 106, figs 22 and 24), having been there regarded (DI GERONIMO & ROBBA, 1989) as an opportunistic species preferring turbid waters.

A specimen of Carrier Shell, the gastropod *Xenophora* sp., has been recognized (RADWAŃSKA & RADWAŃSKI, 2008, pl. 3, fig. 3) by its xenomorphic cast featuring the whole basal plate of one larger balanid shell.

The regular echinoid *Cidaris desmoulini* SISMONDA, 1842, is represented by isolated primary spines of characteristic bead-like sculpture. The best preserved specimen (see Fig. 6) is nearly identical with the one presented by VADÁSZ (1915, pl. 8, fig. 6) from the Neogene (Miocene) of Hungary. To note, VADÁSZ' (1915)

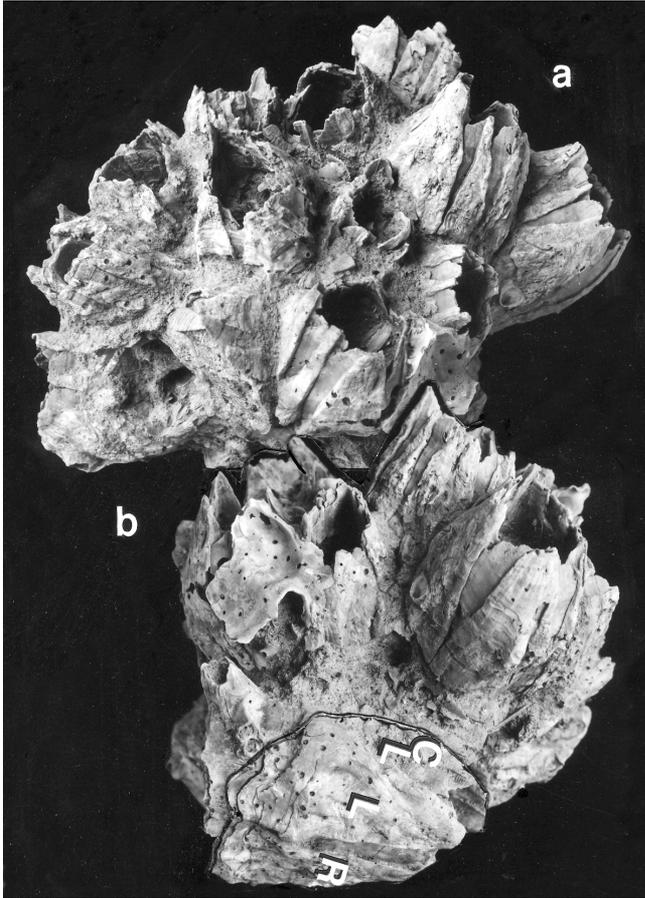


Fig. 5. a-b – Cluster of average-sized balanids *Concavus* (*Concavus*) *concavus* (DARWIN, 1854), taken from two opposite sides, to show its formation upon the shell of a large-sized specimen (lettered are its compartments, see RADWAŃSKA & RADWAŃSKI, 2008) overturned and heavily bored by the sponge *Cliona celata* GRANT, 1826: the cluster itself is bored by *Cliona* less distinctly; Bed No. 9a, nat. size.

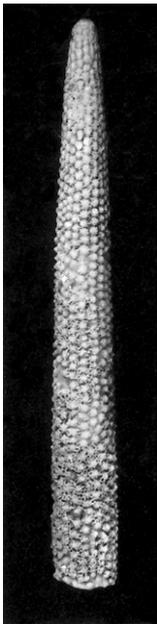


Fig. 6. Primary spine (broken at base) of *Cidaris desmoulinsi* SISMONDA, 1842, from Bed No. 9a; taken x 3.

assignment has recently been objected by KROH (2005, p. XXII, Table 5), who indicated that the so-sculptured primary spines may also belong to another species, *Cidaris schwabenaui* LAUBE, 1871, but this can not be justified. The original specimen, being a compressed test with complete spine canopy (LAUBE, 1871, pl. 16, figs 1-1a) bears long, slender, stick-like spines adorned with thorn-like granules, differing distinctly from these of *Rafina*, which are elongated, slightly fusiform with bead-like granules on the shaft.

Rock-borers

All skeletal material (of balanids, scallops, oysters) in the section has undergone, to a variable extent, the activity of rock-borers. The results of their action, the borings, are attributable (see RADWAŃSKI, 1970, 1977a) to the extant species of: *Cliona celata* GRANT, 1826 (see Fig. 5b), and *C. vastifica* HANCOCK, 1849; to the polychaetes *Polydora ciliata* (JOHNSTON, 1838) and *P. hoplura* (CLAPARÈDE, 1869); as well as to the bivalve *Gastrochaena*, supposedly *G. dubia* (PENNANT, 1777). The latter bivalves have also bored, more or less densely, the limestone pebbles and/or cobbles appearing sporadically in Bed No. 2.

Grazers

The activity of grazers, which produced serial scratches on the shell material when rasping it to get food from its algal coating (see RADWAŃSKI, 1977a, p. 252; and references therein), is evidenced by a unique specimen, once reported from *Rafina* by VOIGT (1977, pl. 1f; re-illustrated by BOUCOT 1990, p. 172, fig. 155A [both with printer's error, as *Ratina*]). This is an oyster valve, the inner surface of which bears parallel sets of minute scratches, interpreted by VOIGT (1977) as grazing traces produced by the radula of a presumed polyplacophoran (chiton), and classified in the range of ichnotaxonomy as a separate ichnogenus, *Radulichnus* VOIGT, 1977.

Burrowers

The activity of burrowers is significantly manifested in three horizons, the two of which are treated as separate beds (Bed No. 6 and Bed No. 12), and the third one having been confined to the topmost part of Bed No. 14 (see Fig. 3). In other beds, indistinct small-sized burrows are met locally, except of Bed. No. 6, in which their maze makes up total bioturbation of the sand.

In the three horizons distinguished, the mass-aggregated burrows reveal the features (canals up to 10-15 cm deep, some of them U-shaped or interconnected horizontally) typical of those produced by the present-day callinassid shrimps of the genus *Upogebia* LEACH, 1814, as reported by ASGAARD *et al.* (1997) from the coasts of Rhodes. A network of such burrows, the best pronounced

in Bed No. 6 (see Fig. 3), is well comparable to that presented by ASGAARD *et al.* (1997, fig. 6), although the studied ones are devoid of the apertural restriction, having been all truncated to an almost flat level.

In Bed No. 12, a network of upogebioid burrows is transected by distinctly larger, tubular burrows (half-a-meter deep, 4-5 cm in diameter), either straight or slightly curved, indistinguishable from those produced by the ghost crabs of the genus *Ocypode* WEBER, 1795, both present-day and ancient (see RADWAŃSKI, 1977a, b, VANNINI, 1980; and references therein). The studied burrows are also truncated at their tops, having been devoid of an entrance plug that is constructed at the burrow's aperture (COWLES, 1908; fide VANNINI, 1980, fig. 19). Noteworthy is, that the ghost crab *Ocypode* is today typical of the tropical/subtropical zone of both Indo-Pacific and Atlantic shores (see FREY & MAYOU, 1971; VANNINI, 1980; CHAKRABARTI, 1981; CASADIO *et al.*, 2005).

ENVIRONMENTAL INTERPRETATION

Sedimentary features of the sequence exposed at Rafina Cliff, as well as its faunal content, indicate that this was formed under shallow-marine conditions, periodically influenced either by storm surges, or by non-deposition. All skeletal material, the giant balanids including, is redeposited, having been transported from diverse offshore habitats, some of which were located just at rocky shores (see pebbles or cobbles bored by bivalves in Bed No. 2). The balanid habitats have been distributed patchily, not having been spread evenly over the whole offshore. In result of storm agitation and redeposition, the balanids in some strata are very infrequent or totally absent (Bed No. 4 at base, Bed No. 10), whereas in others they are quite common (Beds No. 4 and 7), to become mass-aggregated in Bed No. 9.

The overdominance of balanids upon other biota through the regressive sequence of Rafina Cliff allows to interpret (RADWAŃSKA & RADWAŃSKI, 2008) the species *Concavus (Concavus) concavus* (DARWIN, 1854) as an opportunist adaptable to conditions otherwise unfavourable for other settlers. This is well compatible with a general rule that regressions destroy the existing ecospace and cause high stress levels, to favour *r*-selected taxa, characterized i.e. by the great colonizing ability (see, e.g., STEVENS, 1988, pp. 155-156, and references therein).

In early stages of bottom colonization, supposedly when the basin depth decreased, the balanids have crowded mostly on isolated scallop valves (see Fig. 7), the only hard particles then available for the larval settlement (Beds No. 1-5). The scallop valves, usually overgrown by balanids from one side only (outer, or inner), were periodically stirred up by storm agitation and deposited in distal tempestites (Beds No. 2-4). A relatively smaller size of balanids in this part of the sequence (comp. Figs 7 and 8) may indicate either the less favourable life conditions

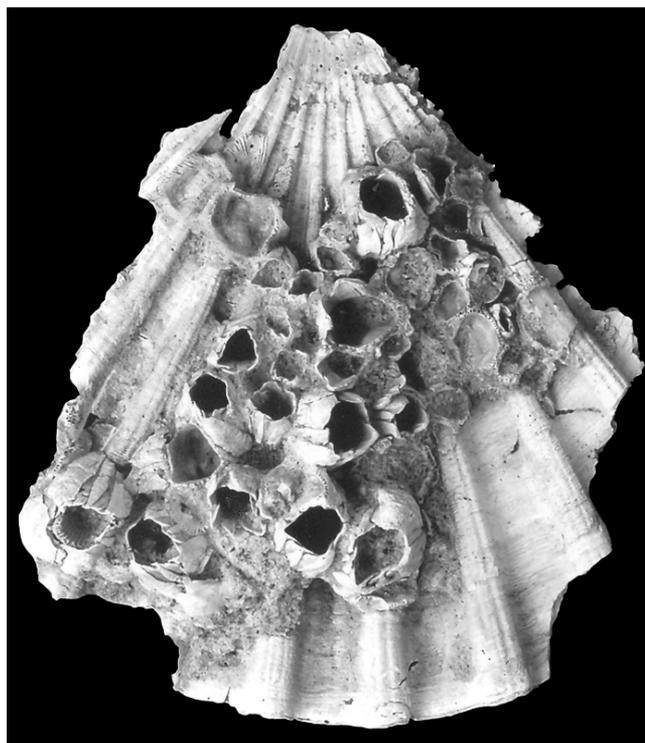


Fig. 7. Isolated scallop valve (outer side) overgrown by small-sized balanids *Concavus (Concavus) concavus* (DARWIN, 1854); Bed No. 4, nat. size.

in their habitats or, otherwise, the catastrophic events acting permanently upon the animals not fully grown yet.

When populations of *Concavus (Concavus) concavus* (DARWIN, 1854) had increased in frequency and density, the balanid hash became the main hard-part material on the bottom, to involve an effect of taphonomic feedback (see RADWAŃSKA & RADWAŃSKI, 2008). Then, the bottom conditions have long been controlled by the profuse growth and intermittent damage of large-sized balanid populations, having been finally swept away from their habitats by storm surges, to be deposited in a proximal (Bed No. 9a) and a distal tempestite (Bed No. 9b).

As all balanids occurring in the sequence of Rafina Cliff are redeposited and abraded, or bioeroded, to a variable extent, their biotopes are thought to have been located in the generally shallower parts of the offshore, possibly up to sub- or intertidal zone.

As concerns the rock-borers, damaging the rocky-shore derived pebbles and/or cobbles, as well as some balanids (see RADWAŃSKA & RADWAŃSKI, 2008), their extant representatives are typical of the shallowest sublittoral zone, ranging just from the shore to a depth of several meters (see RADWAŃSKI, 1970, 1977a). An almost identical assemblage occurs in the Middle Miocene (Badenian) sequence of the Korytnica Basin in the Holy Cross Mountains, Central Poland, where the rock-borers having originally been confined to rocky shores have

subsequently extended their range to the whole basin, precisely to any skeletal material scattered throughout the bottom, when the depth decreased, to reach the sublittoral (? up to intertidal) limit (see BAŁUK & RADWAŃSKI, 1977). Similar rock-borers' assemblages in the Neogene sequences of Europe are known also from the western Mediterranean (see MARTINELL & DOMÈNECH, 1995; DE GIBERT & MARTINELL, 1998; DE GIBERT *et al.*, 1998).

As concerns the burrows, apart from those of the bioturbation maze, these of well-defined shapes are attributable to the two kinds of crustacean decapods, the shrimp *Upogebia* and the crab *Ocypode*, the present-day representatives of which range from the shallow subtidal to intertidal (as *Upogebia*; see ASGAARD *et al.*, 1977), or inter- to supratidal (as *Ocypode*) zone. Of the present-day *Ocypode* burrows, highly different in shape having been dependant on their settlement either nearly to low- or to high-water level (see FREY & MAYOU, 1971; BRAITHWAITE & TALBOT, 1972; RADWAŃSKI, 1977a, b; FÖRSTER & BARTHEL, 1978; VANNINI, 1980; CHAKRABARTI, 1981), the best comparable are those from the upper backshore of the Georgian coast in the United States (see FREY & MAYOU, 1971, pl. 3, figs 1-2 and 5-6).

Noteworthy is the co-occurrence of these two types of burrows at the top of Bed No. 12, where those upogebiid ones are earlier than the ocypodid ones transecting them. Both types of the distinguished burrows are devoid of apertures, indicating high-energy littoral conditions, under

which the burrows were not only produced, but also partly abraded. Moreover, the burrows of the second generation, of *Ocypode*, typical today of the upper backshore, indicate a temporary emersion of the sequence, during which the emerged upogebiid burrows became abraded under supposedly intertidal (beach) conditions.

The extensive calcite cementation of sand in Bed No. 14, propagated horizontally in three distinct horizons, the last of which embraces the densely spaced upogebiid burrows, is morphologically compatible with both present-day and ancient beachrocks (see GINSBURG, 1953; DERMITZAKIS & THEODOROPOULOS, 1975; GISCHLER & LOMANDO, 1997; VOUSDOKAS *et al.*, 2007; RADWAŃSKI & WYSOCKA, 2004). It is assumed that the three horizons have been formed under extremely shallow subtidal and/or intertidal conditions, well comparable to those of the present-day Gulf of Manaar in Ceylon, and of the Middle Miocene (Badenian) seashores of the Holy Cross Mountains, Central Poland (see RADWAŃSKI & WYSOCKA, 2004). During deposition of Bed No. 12, such conditions have been at least three times established repeatedly.

To summarize, the sequence exposed at Rafina Cliff represents in its lower part (Beds No. 1-14 in Fig. 3) the three shallowing-up cycles of offshore deposition, each one terminated by a burrow-bearing horizon indicative of a break in sedimentation and/or emersion (Beds No. 6, 12, and 14). The high-stand episodes, during which the storm-originated deposits (tempestites) were formed (Beds No. 2-4 and 9), should be ascribed to temporary rise of sea level.

All the three cyclothems distinguished are successively thinning upwards to suggest a waning influx of the returning overflood during regression. Moreover, the last of the three cyclothems records the environmental conditions fluctuating sub- to intertidally, signified by the development of beachrocks (Bed No. 14). This evidences the marine regressive sequence having been completed by the load of sediments up to sea level, and their possible temporary exposure to the air.

The uppermost part of the sequence, composed of sandy gravelstones with exotic material, locally trough-stratified (Bed No. 15), indicates a potamogenic (fluvial and/or deltaic) regime that spread over the emerged offshore-to-intertidal regressive sequence. Through a several meters thick series of gravelstones, interbedded with freshwater(?) travertines, this regime is thought to have continued throughout younger Pliocene, possibly till the Lower Pleistocene (see GUERNET & SAUVAGE, 1970; SYMEONIDIS & MARCOPOULOU-DIACANTONI, 1977; GEORGIADES-DIKEOULIA *et al.*, 1979).

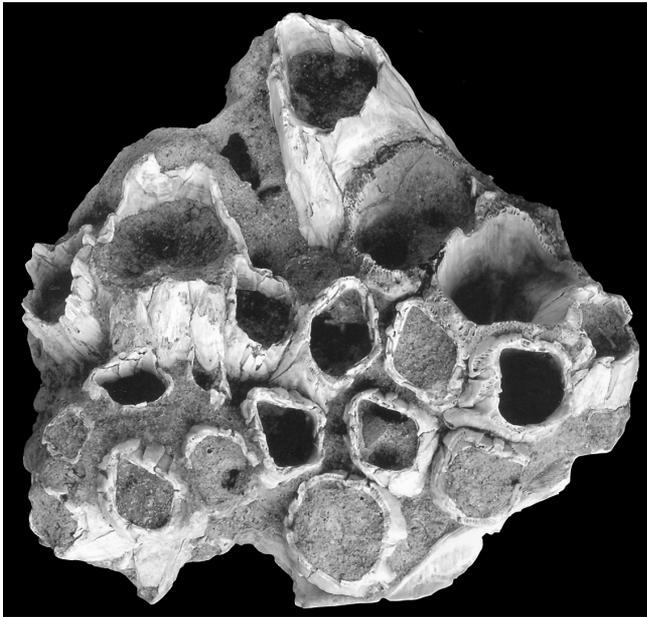


Fig. 8. Group of variably sized balanids *Concavus (Concavus) concavus* (DARWIN, 1854) tightly overgrowing outer side of the isolated valve of a large-sized scallop visible is indistinct orientation (? current orientation; cf. CRISP & STUBBINGS, 1957) of shells, with the carinae paralleling each other more or less accurately (upwards in the photo); Bed No. 9a, nat. size.

PALAEOGEOGRAPHIC CONCLUSIONS

The basement of the Rafina sequence is formed by the 'Pikermi Loams' which constitute the topmost part of the classical Pikermian sequence of Late Miocene (Messinian) age (see GUERNET & SAUVAGE, 1970; SYMEONIDIS & MARCOPOULOU-DIACANTONI, 1977; GEORGIADIS-DIKEOULIA *et al.*, 1979). The vast lowland, upon which the Early Pliocene (Zanclean) transgression has encroached, should thus be interpreted as a karstic polje, marginal to the adjacent Pentelikon Massif. At Pikermian (Messinian) time, all karstic residues/debris have been scoured from this massif by torrential washouts to fill the marginal polje up to an even level by the decline of Pikermian sedimentation. Such interpretation, compatible with recognitions offered by previous authors (see SYMEONIDIS *et al.*, 1979), explains both the torrential-fluvial and the temporary limnic conditions prevailing during the development of the whole Pikermi sequence, as observable at its classical localities, Megalorhema and Chomateres.

The vast polje, marginal to the Pentelikon Massif, when overflowed during the Early Pliocene (Zanclean) transgression, became with its 'Pikermi Loams' the basement upon which marine offshores of Rafina could widely extend and control hydrodynamic conditions favouring profuse colonization by one opportunistic balanid species, *Concavus (Concavus) concavus* (DARWIN, 1854). Its settlement is thought to have smothered the burst of other fauna and, thereby, the Rafina communities became different distinctly from those flourishing coevally in the western Mediterranean, e.g. in the French and Spanish gulfs, being largely the narrow river mouths or estuaria enlarged when overflowed (see DE GIBERT & MARTINELL, 1998; DE GIBERT *et al.*, 1998). The rich sublittoral communities of the Lower Pliocene (Zanclean) have hitherto been recognized only in the broad Lower Nile Valley in Egypt. In this world-famous Kom-el-Shellul Formation, exposed south of Giza, the ubiquitous scallops and oysters are identical with, or closely related to, those of Rafina (compare lists of MITZOPOULOS, 1948, and of FOURTAU, 1898, and HAMZA, 1983); they are associated to the 'giant' specimens of *Clypeaster aegyptiacus* WRIGHT, 1858, the largest fossil echinoid ever known, instead of the giant balanid cirripedes typifying the sequence studied at Rafina Cliff.

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